

# SYMPOSIUM EP09

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Diamond Electronics, Sensors and Biotechnology—Fundamentals to Applications  
November 26 - November 29, 2018

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\* Invited Paper

SESSION EP09.01: Kickoff  
Monday Morning, November 26, 2018  
Hynes, Level 2, Room 207

### 8:15 AM WELCOME BY THE ORGANIZERS

SESSION EP09.02: Diamond Growth and Technology  
Session Chairs: Matthias Schreck and Travis Wade  
Monday Morning, November 26, 2018  
Hynes, Level 2, Room 207

### 8:30 AM \*EP09.02.01

**CVD Diamond Synthesis—How to Meet Our Device Expectations?** Philippe Bergonzo<sup>1,2</sup>; <sup>1</sup>Seki Diamond Systems, San Jose, California, United States; <sup>2</sup>Electronic and Electrical Engineering Dpt, University College London, London, United Kingdom.

Diamond is an exceptional material combining superlative properties like superhardness, superconductivity, high thermal conductivity, biocompatibility, radiation resistance, and unique optical properties etc. These advantages make diamond an excellent material to reply to a broad range of applications, that include thermal coatings, electrodes, windows, sensors, detectors, electronic devices, as well as quantum devices for a variety of applications. The synthesis of diamond is now a well-established technique, and especially when using CVD (Chemical Vapor Deposition) with a range of diamond growing machines readily commercially available at reasonable prices, as demonstrated by the exceptional recent rise of diamond foundries created to reply to a booming synthetic gemstone market.

Still, beyond gemstone fabrication, advances in growth technologies have made it possible to purposely grow synthetic diamond with tuned performances that go beyond that of other materials, and ultimately well below those of more conventional diamonds. This includes for example large area doped diamond films coatings on non-diamond substrates, or films of specific crystalline structures, or with control defect incorporation, at the nanoscale level, or also isotopically purified diamonds for quantum applications, etc.

The step from conventional diamond growth to optimized materials has required a range of technological solutions that have been developed, including for example the possibility to perform 3D structuration of diamond films, as well as the patterning of diamond growth over large area substrates, or the fabrication of ultrathin diamond membranes structured as photonics crystals, or of flexible diamond foils for implant applications, etc. All such approaches have been made compatible with clean room nanotechnology environments to be able to tune the material to the ultimate device fabrication needs. This presentation will review a portfolio of such technological approaches in order for the diamond grower to be able to conceive devices that reply to his application needs.

### 9:00 AM EP09.02.02

**Single Crystal Diamond Plates Grown by a Combination of Mosaic Technique and Lateral Growth** [Ramon D. Diaz](#)<sup>1</sup>, Aaron Hardy<sup>2</sup>, Elias Garratt<sup>1, 2</sup> and Timothy A. Grotjohn<sup>1, 2</sup>; <sup>1</sup>Michigan State University, East Lansing, Michigan, United States; <sup>2</sup>Fraunhofer Center for Coatings and Diamond Technologies, East Lansing, Michigan, United States.

The electrical, mechanical, and thermal properties of diamond make it a promising material for new generation electronic devices. One of the challenges is the need for fabricating larger size Single Crystal Diamond (SCD) wafers with minimal defects. In this study, SCD plates were successfully grown based on the mosaic technique combined with conditions known for enhanced lateral growth. In earlier works [1] the plates were tiled together using substrates created by a process consisting of ion implantation followed by growth and electrochemical separation. The approach in this work is different in that a starting substrate is cut in two, then each of the two pieces are grown larger laterally followed by a growth that stitches them back together with a larger area. A series of steps were taken to ensure good crystallographical orientation, starting with laser cutting the tiles from the same 3.5 mm x 3.5 mm x 1.4 mm HPHT (High Pressure High Temperature) seed. The original area of the two substrates was increased by growing a layer of diamond via MPACVD (Microwave Plasma-Assisted Chemical Vapor Deposition) using a pocket configuration which favors lateral growth [2][3]. The grown tiles are polished and kept in aligned contact by their base with a polycrystalline diamond plate used as reference on the holder during growth. This step produced a continuous layer diamond across the two pieces. The grown together substrate was then re-polished and re-grown multiple times by MPACVD process until the contact (stitched region) interface disappeared, effectively merging the tiles back into a single crystal. Defect densities from the grown layers were analyzed by etch pit counting and birefringence measurements. X-ray rocking curve mapping of the sample shows a maximum misorientation spread of 0.2 degrees, with an average mosaicity of  $0.019 \pm 0.008$  degrees along the surface, demonstrating the feasibility of combining the developed mosaic technique with known lateral growth conditions for increasing the area of SCD wafers.

The authors would like to acknowledge funding for this work from MIT Lincoln Laboratory. X-Ray rocking curve measurements were provided by Rigaku, and X-Ray topography measurements were performed at APS, Argonne National Laboratory.

[1] Yamada, H., A. Chayahara, Y. Mokuno, Y. Kato, and S. Shikata. "A 2-in. Mosaic Wafer Made of a Single-Crystal Diamond." *Applied Physics Letters* 104, no. 10 (2014): 102110. <https://doi.org/10.1063/1.4868720>.

[2] S. Nad, A. Charris, and J. Asmussen. "MPACVD Growth of Single Crystalline Diamond Substrates with PCD Rimless and Expanding Surfaces." *Applied Physics Letters* 109, no. 16 (2016): 162103. <https://doi.org/10.1063/1.4965025>.

[3] A. Charris, Toward the Rapid Growth of High-Quality, Polycrystalline Rimless, and Large Area Single Crystal Diamond Substrates. Michigan State University, 2017.

### 9:15 AM EP09.02.03

**Development of Kinetic Monte Carlo Modelling and Visualisation of CVD Diamond Growth** [Max D. Williams](#)<sup>1, 2</sup>, Neil L. Allan<sup>1</sup> and Paul W. May<sup>1</sup>; <sup>1</sup>School of Chemistry, University of Bristol, Bristol, United Kingdom; <sup>2</sup>Diamond Science and Technology CDT, University of Warwick, Coventry, United Kingdom.

Using a simplified kinetic Monte Carlo (kMC) model of CVD diamond growth, the diamond and computational chemistry groups at the University of Bristol have previously reported simulating many atomic layers of diamond growth at relatively low computational cost. These simulations have been found to reproduce many of the growth features seen experimentally, including growth rates, while keeping the computational time required on the order of hours, in contrast to more complicated models.<sup>1</sup> However, one limitation of such a simplified model is the use of a cubic representation of the diamond atomic lattice. Although this allows low calculation times and simplified methods, the geometries of specific adsorbates or surface defects thought to be important in the diamond growth mechanism cannot be correctly modelled.

We now report on progress in transitioning the simulation from a simple cubic lattice to a true tetrahedral diamond structure, inheriting some of the methods and approximations on which the original model relied for maximum performance and simplicity. This more realistic representation for the diamond lattice allows implementation and testing of more complicated CVD growth reaction schemes, with application of modern software developmental strategies maintaining the model's computational efficiency. Visualisation of the diamond surface as CVD growth progresses in true tetrahedral co-ordination is also now possible, allowing robust and powerful analysis of implemented reaction schemes and their effect on surface morphology development as a function of time.

In this presentation we shall use animations and videos of the simulations to show how the model can be used to test potential reaction schemes, as well as understand growth mechanisms and the associated energy barriers from literature, and determine their contribution to growth rate, surface morphology and defect formation. The ultimate aim of this work is to use measured parameters from a diamond CVD system (gas mixture, pressure, temperature, etc.), to predict accurately the expected growth rate, morphology, grain size, and even defect types and locations within a CVD diamond film.

#### References

<sup>1</sup> W. Rodgers, P. May, N. Allan and J. Harvey. *J. Chem. Phys.* 142 (2015) 214707.

### 9:30 AM EP09.02.04

**High Quality CVD Diamond Growth on Gallium Nitride Using a Novel 2-Step Micro/Nano Diamond Seeding Method** [Afaq Habib Piracha](#)<sup>1</sup>, Edmund Smith<sup>1</sup>, Paul W. May<sup>1</sup>, Chao Yuan<sup>2</sup>, Fabien Massabuau<sup>3</sup> and Martin Kuball<sup>2</sup>; <sup>1</sup>School of Chemistry, University of Bristol, Bristol, United Kingdom; <sup>2</sup>Center for Device Thermography and Reliability, University of Bristol, Bristol, United Kingdom; <sup>3</sup>Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom.

Diamond films deposited onto GaN are useful for heat dissipation in GaN microwave electronics, in particular GaN based MMICs and HEMTs. GaN on diamond will underpin future high-power radio frequency and microwave communications, space and defence systems, paving the way towards 5G and 6G mobile-phone networks and more comprehensive radar systems. However direct deposition of CVD diamond onto GaN (*i.e.* without a barrier layer being present) is difficult due to the etching of the GaN in the hot CVD environment and poor film adhesion<sup>1</sup>. Moreover, the standard seeding method using detonation nanodiamond results in the first few nm of the diamond film being composed of nm-sized grains with poor thermal conductivity. This creates an undesirable thermal barrier between the active GaN device and the higher quality diamond deposited at later stages of growth which acts as the heat spreader.

To overcome this issue, a novel seeding method was developed to improve the coverage of diamond particles onto GaN on silicon wafers while maintaining an effective thermal interface between the diamond and the GaN.

We describe the optimised seeding procedure as well as the procedure to grow diamond films onto epitaxial GaN. A seeding was performed using an electrospray technique in which the wafers were mounted on the rotating copper disk and diamond solution was filled in a tube that sprayed on the targeting wafers by applying high accelerating voltage. This method results in a uniform distribution of diamond solution onto the wafers and eventually dried to give a homogeneously covered mixture of nano/micro diamond particles on GaN wafer.

A method whereby a 2-step seeding process is used to ensure a high thermal conductivity layer is deposited on a GaN substrate: (1) Seed the surface using microdiamonds (1-10  $\mu\text{m}$ ), using any standard method optimised for dense monolayer coverage. This provides the high thermal conductivity interface. (2) Seed a second time, this time using nanodiamonds (4 nm), using any standard method optimised for dense monolayer coverage. This fills in the voids and prevents the GaN from etching in the subsequent diamond deposition process.

Diamond growth was done in both standard hot filament CVD reactor (HFCVD) and microwave plasma CVD reactor (MPCVD) and the results were compared. We will present results including SEM and thermal measurements showing continuous high-quality diamond layers without pinholes. Diamond films were grown after 2-step seeding method with thickness ranging from 1-50  $\mu\text{m}$ . 2-step seeding seems to work nicely, with reasonably adherent, conformal diamond layers up to 50  $\mu\text{m}$  thick being deposited onto GaN.

#### References

P.W. May, H.Y. Tsai, W.N. Wang and J.A. Smith, "Deposition of CVD Diamond onto GaN", *Diam. Relat. Mater.* **15** (2006) 526.

#### 9:45 AM EP09.02.05

**Controlled Gold Nanoparticle Formation During the Growth of Boron Doped, Nanocrystalline Diamond on Gold Substrates** [Shannon S. Nicley](#)<sup>1,2,3</sup>, Sien Drijkoningen<sup>1,2</sup>, Paulius Pobedinskas<sup>1,2</sup> and Ken Haenen<sup>1,2</sup>; <sup>1</sup>Institute for Materials Research (IMO), Hasselt University, Diepenbeek, Belgium; <sup>2</sup>IMOMECE, IMEC vzw, Diepenbeek, Belgium; <sup>3</sup>Department of Materials, University of Oxford, Oxford, United Kingdom.

The use of diamond grown onto patterned gold substrates for Fourier Transform Infrared (FTIR) spectroscopy has proved to be an effective characterisation method for undoped diamond functionalised with biomolecules,<sup>1</sup> however insulating diamond substrates cannot be used for electrochemical grafting, which requires a conducting substrate.<sup>2</sup> In this study, we have grown well-adhered boron doped nanocrystalline diamond (B:NCD) thin films over continuous gold (Au) substrates, which formed Au nanoparticles (AuNPs) during the initial stages of growth. These AuNPs were then subsequently overgrown by the diamond films. The formation of AuNPs by annealing thin films of gold has been of significant recent interest, for use as catalysts for growing nanowires and for plasmonics. Arrays of AuNPs could be used to maximise the absorption in the active layer of photovoltaic (PV) cells, where the particle size and shape are critical for precisely tuning the light scattering and trapping to maximise the PV performance. Thin film annealing is a high throughput, low contamination method of AuNP formation, but the diameter range of the particles obtained this way is still broad, and their position is uncontrolled, so a better understanding and control of the formation method of thin film annealed AuNPs is needed.

AuNPs of approximately 1  $\mu\text{m}$  diameter formed during microwave plasma assisted chemical vapour deposition (MPACVD), and these were overgrown by diamond. We will show that the formation of AuNPs is affected by the surface treatment. The initial nucleation of the particles can be decreased by pretreatment with water or UV-ozone oxygen treatment. The size of the AuNPs under the diamond film can be increased to approximately 2  $\mu\text{m}$  in diameter by UV-ozone treatment of the surface prior to growth.

Low temperature diamond growth (LTDG) is an area of active research interest, as processing at low temperatures is important for growth on substrates with properties such as high thermal expansion coefficients, low melting temperatures, and high thermal diffusivities. Among the possible routes, surface wave plasma linear antenna (LA) deposition with oxygen-containing gasses (such as CO<sub>2</sub>) in the gas mixture is considered to be the most promising LTDG growth process.<sup>3</sup> We will show that growing a 50 nm NCD nucleation layer at low temperature in the presence of CO<sub>2</sub> in an LA reactor suppresses the formation of AuNPs under the diamond film, even after subsequent B:NCD overgrowth. We are therefore able to grow B:NCD over Au substrates, with control over the formation and size of overgrown AuNPs.

#### References

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2. J. Raymakers, *et al.*, *J. Phys. Chem. C*, **121**, 23446-23454 (2017)

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4. S.S. Nicley, S. Drijkoningen, P. Pobedinskas, K. Haenen "Controlled Gold Nanoparticle Formation During the Growth of Boron Doped, Nanocrystalline Diamond on Gold Substrates" *Submitted* (2018)

#### 10:00 AM BREAK

#### 10:30 AM \*EP09.02.06

**Thick Single Crystal Diamond Growth with Stage Height Control** [Mariko Suzuki](#) and Kazuo Tsugawa; Seki Diamond Systems, Cornes Technologies Ltd., Tokyo, Japan.

Synthetic diamond has been developed for many applications such as, traditionally, tools, optical windows and heat spreaders. Optical and electronics sensors and devices including high power electronic devices and quantum devices have been advanced by developing CVD diamond growth technique. As another aspect, CVD diamond has attracted much attention for gem stone application, "lab grown diamond", and the market is rapidly growing. For these industrial and commercial use, large and thick high quality diamonds are demanded.

We have been developing and providing microwave plasma CVD systems specialized for diamond growth over many years. Our current target is to develop growth of thick single crystal diamonds with our clamshell shaped MWPCVD system equipped with automatically continuously moving (along with vertical axis) stage during CVD growth. This new height-controllable stage can maintain a constant configuration between diamond substrates, plasma, and an optical pyrometer to realize stable measurements of substrate temperature during a long duration of CVD growth. It also enables to change plasma shape to provide suitable temperature to each of multiple substrates and then temperature uniformity in large area.

In this talk, we would like to introduce the above-mentioned new equipment and our recent progress toward thick and large diamond growth with it.

#### 11:00 AM EP09.02.07

**Crystallographic Orientation Dependent Reactive Ion Etch in Single Crystal Diamond** [Ling Xie](#), Tony Zhou and Amir Yacoby; Harvard University, Cambridge, Massachusetts, United States.

Diamond serves as a host material for a variety of atomic defects, some of which show interesting quantum-mechanical spin and optical properties. The presence of such atomic color centers has given diamond an important role in magnetometry<sup>[1]</sup> and photonics<sup>[2]</sup>. For many such applications, optimizing the diamond structure in relation to the color center on the micro and nanoscales and along particular crystal directions is important<sup>[3]</sup>.

In this work (*Advanced Materials* **2018**, *30*, 1705501), we demonstrate that anisotropic etching along multiple crystal directions in diamond is achieved by controlling the oxygen plasma conditions in an inductively-coupled reactive ion etcher (ICP-RIE). Further, we present the underlying etching principle to shed light onto diamond crystal direction dependent etching mechanism. Using this principle, Si-KOH etch is resembled on diamond as an encouraging sign that the principle can be applied to other single crystal materials. With the principle presented here, large taper-angled nanopillars can be fabricated. Beyond higher fluorescence collection efficiency, the larger taper angle of nanopillars strongly enhances the mechanical strength of the structure. This is particularly important in NV center-based scanning probe applications where the diamond nanopillar is scanned in contact over the sample surface. In summary<sup>[4]</sup>, the crystal direction dependent reactive ion etching principle is presented for selectively revealing crystal planes in monocrystalline diamond by varying etching conditions in an ICP-RIE system. We believe that the etching principle presented here is applicable to other single crystal materials that hold crystallographic anisotropy and in other types of dry etching systems, such as reactive ion beam etch. This principle will enable forming a wide range of shapes in different single crystal materials for a broad variety of applications.

#### References

- [1] T. X. Zhou, R. J. Stöhr, A. Yacoby, *Appl. Phys. Lett.* **2017**, *111*, 163106.
- [2] T. M. Babinec, B. J. M. Hausmann, M. Khan, Y. Zhang, J. R. Maze, P. R. Hemmer, M. Lončar, *Nat Nano* **2010**, *5*, 195.
- [3] S. A. Momenzadeh, R. J. Stöhr, F. F. de Oliveira, A. Brunner, A. Denisenko, S. Yang, F. Reinhard, J. Wrachtrup, *Nano Letters* **2015**, *15*, 165.
- [4] L. Xie, T. X. Zhou, R. J. Stöhr, A. Yacoby, *Advanced Materials* **2018**, *30*, 1705501.

#### 11:15 AM EP09.02.08

**Effect of Chemical Mechanical Polishing Time on Subsurface Damage and Device Specification in Diamond Substrate** [Yutaka Kimura](#)<sup>1</sup>, Seongwoo Kim<sup>1</sup>, Makoto Kasu<sup>2</sup>, Satoshi Masuya<sup>2</sup>, Kenjiro Ikejiri<sup>1</sup> and Koki Oyama<sup>1</sup>; <sup>1</sup>Diamond development, Adamant Namiki Precision Jewel Co., Ltd., Yuzawa, Japan; <sup>2</sup>Saga University, Saga, Japan.

Diamond can be used for wide range of applications, not only for jewelry. Diamond has a lot of attentions to be an ultimate semiconductor material because of its physical properties like as the wide band gap and high carrier mobility. The ultimate semiconductor devices, such as high frequency device and high-power transistor, are also expected application by these physical properties<sup>1,2</sup>. In semiconductor device fabrications, damage- and roughness-free substrate surface is essential. For this purpose, in conventional semiconductors, chemical mechanical polishing (CMP) is widely used. However, in diamond there are very few reports of CMP. In this work, we perform CMP on single-crystal diamond substrates and investigate its effect on the surface properties.

The samples were HPHT single crystal diamond (001) (~4 x 4 x 0.5 mm<sup>3</sup>). First, all the surfaces were mechanical polished (MP) to adjust the thickness, the off angle, the roughness. Next, CMP was performed on the diamonds with different processing time; 0 h (MP only), 5 h, 50 h and 100 h. The surface roughness before DC plasma CVD growth was less than 0.2 nm. Finally, the diamond films were homoepitaxially grown on the MP and CMP-treated diamond substrates for 10 hours by DC-plasma CVD method.

In synchrotron radiation X-ray section topography observation, we have found different contrast between the substrate subsurface with and without CMP. Further, we confirmed pits on the CVD diamond surface grown on the substrate without CMP. However, as the CMP procession time increased, the pit density decreased. Eventually, on the surface for 100 h CMP, no pits were observed. From these results, we concluded that the subsurface damage leads to pit formation in homoepitaxial growth, and CMP on the substrate is effective to prevent pit formation in CVD diamond growth.

The sheet resistance was carried out by Hall effect measurement. We found that the sheet resistance decreased with increasing CMP time. CMP is important technique for diamond device.

- 1) H. Aida et al, *Appl. Phys. Express* **9**, (2016) 035504.
- 2) M. Kasu et al., *Appl. Phys. Express* **5** (2012) 025701.

#### 11:30 AM EP09.02.09

**Direct Measurement of the Diamond Nucleation Landscape Reveals Classical and Non-Classical Features** [Matthew A. Gebbie](#) and Nicholas A. Melosh; Stanford University, Stanford, California, United States.

Nucleation is a core scientific concept, describing the formation of new phases and materials. While classical nucleation theory is often applied to understand diamond nucleation, measured nucleation rates often greatly exceed classical predictions, and nanoscale nucleation energy landscapes have never been directly measured, particularly under the extreme conditions of diamond growth. I will present a method for directly measuring the nucleation energy landscape of diamond, a previously inaccessible regime in a core physical process. Using a series of diamondoid molecules as atomically-defined proto-nuclei, we find that 26 carbon atom clusters, which do not contain a single bulk atom, are post-critical nuclei and measure the nucleation barrier to be four orders of magnitude lower than prior bulk estimates. These data support both classical and non-classical concepts for multi-step nucleation and growth during the gas phase synthesis of diamond and other semiconductors, and I will discuss insights to guide the growth of diamond nanomaterials for advanced applications. More broadly, our work supports recent theoretical proposals of multi-step nucleation pathways with metastable critical nuclei that fundamentally differ from the final bulk phase in processes ranging from nanoparticle synthesis to cloud formation.

#### 11:45 AM EP09.02.10

**The Effect of Methane Concentration on Surface Morphology and Doping Efficiency of Heavily Boron-Doped Single Crystal Diamond Layers** Rozita Rouzbahani<sup>1,3</sup>, [Shannon S. Nicley](#)<sup>1,3,2</sup>, Paulius Pobedinskas<sup>1,3</sup> and Ken Haenen<sup>1,3</sup>; <sup>1</sup>Institute for Material Research (IMO), Hasselt University, Hasselt, Belgium; <sup>2</sup>Department of Materials, University of Oxford, Oxford, United Kingdom; <sup>3</sup>IMOMEC, IMEC vzw, Diepenbeek, Belgium.

To develop diamond-based high-power electronics, several challenges must be overcome. One of these is the growth of high quality heavily ( $p^+$ ) B-doped single crystal diamond (SCD) layer. It has been reported that deterioration of film morphology, due to the presence of defects, prevents achieving high boron concentration ( $10^{21}$  cm<sup>-3</sup>) in the diamond lattice.<sup>1</sup> The impact of [C]/[H] ratio on the surface quality and electrical properties of B-doped SCD grown by microwave plasma-enhanced CVD (MW PE CVD) is investigated in this study. Heavily B-doped SCD layers were grown in a home-built CVD reactor on 33 mm<sup>2</sup> lb (100)-oriented HPHT substrates. Growth was performed in a conventional [CH<sub>4</sub>]/[H<sub>2</sub>] plasma (0.5%, 1%, 2%, and 3%), with trimethylboron as the boron source, with a constant 997 ppm [B]/[C] ratio used for all of samples. The aim was to analyze the effect of methane concentration on the electrical properties of grown films. Diamond deposition by CVD constitutes a delicate balance between diamond growth and etching by hydrogen. Atomic force and optical microscopies confirmed that etching was dominant for B-doped diamond growth at lower [C]/[H] ratio (0.5%), as seen in the morphology from the appearance of etch pits. This effect was observed at the lower [B]/[C] ratio than what has been previously observed in literature.<sup>2</sup> At a higher [C]/[H] ratio (1%), high-quality  $p^+$  B-doped SCD layers were obtained. In Raman spectra, a broad peak was observed at the wavenumber 500 cm<sup>-1</sup>, the width of which is proportional the boron concentration in diamond.<sup>3</sup> Fourier transform Infrared (FTIR) spectroscopy also gives an estimate of

boron content as has been demonstrated by several research groups<sup>4,5</sup> for  $p^+$  B-doped samples. The boron concentrations estimated by Raman and FTIR spectroscopies were compared to the results of Hall effect which gave high boron incorporation levels but lower than what was estimated by the Raman and FTIR methods. The overestimated boron concentration could be due to the imperfect transmission through the samples and the possible error in the measurement of grown thickness. Even with this error, the boron concentrations which were measured by Hall effect showed the same  $[C]/[H]$  ratio dependence as determined by the Raman and FTIR methods, with the sample grown at 3%  $[CH_4]/[H_2]$  showing a higher boron incorporation than those grown at lower  $[CH_4]/[H_2]$ .

#### References

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2. A. Fiori, *et al.*, *Diam. Rel. Mat.* **76** (2017), 38-43
3. M. Bernard, *et al.*, *Diam. Relat. Mater.* **13** (2004) 282-286
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SESSION EP09.03: Doping and Quantum-Effects I  
Session Chairs: Mutsuko Hatano and Shannon Nicley  
Monday Afternoon, November 26, 2018  
Hynes, Level 2, Room 207

#### 1:30 PM \*EP09.03.01

**Nanodiamond Quantum Sensors for Life Science** Ryuji Igarashi<sup>1</sup>, Takuya Genjo<sup>2</sup>, Takahiro Fujisaku<sup>2</sup>, Daiki Terada<sup>2</sup>, Ryotaro Tanabe<sup>2</sup>, Sotoma Shingo<sup>3</sup>, Yoshie Harada<sup>3</sup> and Masahiro Shirakawa<sup>2</sup>; <sup>1</sup>National Institute for Quantum and Radiological Science and Technology, Chiba, Japan; <sup>2</sup>Kyoto University, Kyoto, Japan; <sup>3</sup>Osaka University, Suita, Japan.

A cell is a precision microsystem made up of a variety of micro- and nanocomponents, such as organelles and biomacromolecules. The cell system is governed by nanometer-scale physical and chemical properties with spatial and temporal variations. This means that the nanoscale measurements can provide a wealth of information about biological functions. However, the sensitivity and stability of measurement heavily depend on the sensor size. Therefore, nanometer-sized small sensors that can be used in cells were generally unreliable. Here, we describe intracellular measurement techniques using fluorescent nanodiamond as a quantum sensor for nanoscale chemical and physical properties. The nanodiamond quantum sensors are promising not only in advancing knowledge in fundamental science but also in technological applications, in the same way that small sensors empowered smartphones and self-driving cars, and thus, has a potential to open new avenues for nanobioscience and nanoindustry.

#### 2:00 PM EP09.03.02

**Superconducting Boron-doped Diamond Josephson Junction Operating up to 7.0K** Shotaro Amano<sup>1</sup>, Taisuke Kageura<sup>1</sup>, Ikuto Tsuyuzaki<sup>1</sup>, Minoru Tachiki<sup>2</sup>, Shuuichi Ooi<sup>2</sup>, Shunichi Arisawa<sup>2</sup>, Yoshihiko Takano<sup>2</sup> and Hiroshi Kawarada<sup>1,3</sup>; <sup>1</sup>Waseda University, Tokyo, Japan; <sup>2</sup>MANA National Institute for Materials Science, Tukuba, Japan; <sup>3</sup>The Kagami Memorial Laboratory for Materials Science and Technology, Shinjuku, Japan.

Superconducting quantum interference device (SQUID), which is composed of superconducting loop with Josephson junction, is widely used for ultra-high sensitive magnetometers. One of the current problems is that conventional superconducting material like Nb is fragile. Superconducting boron-doped diamond is robust and resistant to contact, oxidation, and deterioration, so it is suitable material for robust SQUID. We previously fabricated step-edge structure Josephson junction [1], but the superconducting transition temperature ( $T_C$ ) was lower than 4.0K. It is essential to operate above liquid helium temperature (4.2K) for application to SQUID. So in this research, we report the Josephson junction composed only of (111) film with operating up to 7.0K. We fabricated a Josephson junction with weak links in intermittent (111) plane. Weak links were formed at the interfaces of the (111) superconducting diamonds across trench region. This trench was formed on the (111) diamond substrate by Focused Ion Beam. The trench had a width of 200 nm and a depth of 30 nm. Then a superconducting boron-doped layer with a thickness of 500 nm was selectively grown across the trench by microwave plasma enhanced chemical vapor deposition method.

We investigated the temperature dependence of resistance ( $R$ - $T$ ), two-step superconducting transitions were observed at 10.2K and 7.0K, corresponding to  $T_C$  of the boron-doped diamond grown from the substrate and the trench, respectively. This operating temperature is nearly twice the previous value [1] and is also comparable to that of Josephson junction with Nb, which is generally used for SQUID. This is because this Josephson junction was composed of only (111) diamond with  $T_C=10K$  whereas the step-edge structure included (001) with  $T_C=4K$  [2]. The  $I$ - $V$  characteristic had no hysteresis and showed DC Josephson effect. The critical current ( $I_C$ ) was 0.03 mA and  $I_C R_n$  was 0.15 mV at 4.2K. This value is comparable to that of Nb SQUID. Shapiro steps were observed up to 7.0K more clearly than before. The interval between steps was in good agreement to the theoretical value calculated from the frequency of microwave and flux quantum ( $\Phi_0=2 \times 10^{-15} Wb$ ).

We fabricated the Josephson junction composed only of (111) diamond and observed both the DC and AC Josephson effect up to 7.0K. These results means that this Josephson junction has the capability of operating above liquid helium temperature. We strive to demonstrate the operation of the SQUID and assemble this SQUID into a Scanning microscope.

This work was supported by JSPS Grant-in-Aid for Scientific Research (S)26220903, (B)17H03526 and Research Activity start-up 17H07192. This study was supported by NIMS Nanofabrication Platform in Nanotechnology Platform Project sponsored by MEXT, Japan.

[1] I. Tsuyuzaki, H. Kawarada *et al.*, *MRS Fall 2017*

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#### 2:15 PM EP09.03.03

**<sup>1</sup>H NMR Detection on Nitrogen Terminated Diamond by Shallow Nitrogen Vacancy Centers** Takahiro Sonoda<sup>1</sup>, Sora Kawai<sup>1</sup>, Hayate Yamano<sup>1</sup>, Jorge J. Buendia<sup>1</sup>, Taisuke Kageura<sup>1</sup>, Yu Ishii<sup>1</sup>, Kiro Nagaoka<sup>1</sup>, Ryosuke Fukuda<sup>1</sup>, Takashi Tani<sup>1</sup>, Moriyoshi Haruyama<sup>2,3</sup>, Keisuke Yamada<sup>2</sup>, Shinobu Onoda<sup>2</sup>, Wataru Kada<sup>3</sup>, Osamu Hanaizumi<sup>3</sup>, Alastair Stacey<sup>4</sup>, Kazuhiro Kanda<sup>5</sup>, Masaharu Uemura<sup>5,6</sup>, Tokuyuki Teraji<sup>7</sup>, Junichi Isoya<sup>8</sup>, Shozo Kono<sup>9</sup> and Hiroshi Kawarada<sup>1,9</sup>; <sup>1</sup>Waseda University, Shinjuku, Japan; <sup>2</sup>National Institute of Quantum and Radiological Science and Technology, Takasaki, Japan; <sup>3</sup>Gunma University, Kiryu, Japan; <sup>4</sup>University of Melbourne, Parkville, Melbourne, Victoria, Australia; <sup>5</sup>Laboratory of Advanced Science and Technology for Industry, University of Hyogo, Koto Kamigori, Japan; <sup>6</sup>Synchrotron Analysis LLC, Wadamia-dori, Hyogo-ku, Kobe, Japan; <sup>7</sup>National Institute for Materials Science, Tsukuba, Japan; <sup>8</sup>University of Tsukuba, Tsukuba, Japan; <sup>9</sup>Kagami Memorial Research Institute for Materials Science and Technology, Shinjuku, Japan.

Nitrogen vacancy (NV) center in diamond is expected as a highly sensitive magnetic sensor for nanoscale NMR [1]. Since signal decays as  $1/r^3$ , where  $r$  is the distance from a magnetic field source, shallow NV centers must be fabricated. In order to improve properties of shallow NV centers, surface terminations such as O-terminations [2, 3] have been focused on. Recently, a theoretical calculation implied that N-terminated surface shows positive electron affinity (PEA) and contributes to stabilization of negatively charged state of shallow NV centers [4]. We have already reported that N-termination by nitrogen radical exposure leads to stabilization of negatively charged states of shallow NV centers [5]. The next step of our research is to investigate the applicability of N-terminated surface to NMR detection. In the previous study,  $N_2$  gas which contains 4%  $H_2$  gas was used as the radical source intending surface cleaning. However, there is a possible concern that the  $H_2$  will cause formation of C-H bond and “N/H” structure, which exhibits lower PEA (+0.32 eV) than that of “full N” structure (+3.46 eV) [4]. Here, we investigated properties of shallow NV centers under N-terminated surface which was fabricated by N radical exposure using 100%- $N_2$  gas.

$^{12}C$  enriched high purity diamond films were homoepitaxially grown on (001) substrates [6]. Single NV centers were created by low energy (2.5 keV) N ion implantation and subsequent thermal annealing. Hot acid treatment was conducted for surface cleaning and O-termination. Then, formation of N-terminated surface was achieved by N radical exposure, which is generally used for molecular beam epitaxial (MBE) growth of III-nitride. 100%- $N_2$  gas was used as the radical source. Charge stability of shallow NV centers was evaluated by Rabi oscillation contrast and coherence time  $T_2$  was estimated by Hahn echo measurements. Average Rabi contrast was 0.20 after hot acid treatment and 0.34 after N radical exposure. The longest coherence time under the N-terminated surface was  $\sim 10 \mu s$ . XY8 measurements for  $^1H$  NMR detection were conducted on the N-terminated surface. Depth of the NV center estimated from the  $^1H$  NMR signal [7] was 10.0 nm. In conclusion, negatively charged states of shallow NV centers were stabilized by N radical exposure using 100%- $N_2$  gas, and we successfully detected  $^1H$  NMR on the N-terminated surface by shallow NV centers.

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#### Acknowledgements

We thank Dr. Liam P. McGuinness and Prof. Fedor Jelezko for their help in building CFM setup.

#### 2:30 PM EP09.03.04

##### **Synchrotron Based Spectroscopies Confirm the Surface Modification of Nanoscale Diamond with Low-Z Molecular Precursors** Cynthia

Melendrez<sup>1</sup>, Perla J. Sandoval<sup>1</sup>, Jocelyn Valenzuela<sup>1</sup>, Polo Tran<sup>1</sup>, Karen Lopez<sup>1</sup>, Daniela Barrera<sup>1</sup>, Solomon Adjei II<sup>1</sup>, Virginia Altoe<sup>3</sup>, Dennis Nordlund<sup>2</sup> and Abraham Wolcott<sup>1</sup>; <sup>1</sup>San Jose State University, San Jose, California, United States; <sup>2</sup>SLAC National Accelerator Laboratory, Menlo Park, California, United States; <sup>3</sup>The Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, California, United States.

The fluorescent nitrogen vacancy center in diamond is a powerful imaging tool of both magnetic and electric fields with nanometer spatial resolution. Tracking of individual NVCs hosted in nanoscale diamond is possible because of their electron-spin readout properties and opens new avenues for imaging in cells and tissues. Fluorescent nanoscale diamond (FND) is produced via ball-milling of macroscopic high-pressure high-temperature diamond and has electronic and surface properties that are nearly identical to bulk diamond. While FNDs are attractive for biolabelling due to their chemical inertness and lack of cytotoxicity, few chemical routes exist to modify their surface and most routes focus on carboxylate chemistry. Here we use gas phase and wet chemical techniques to modify the surface with amines, boranes and silica and provide definitive chemical analysis with surface sensitive spectroscopies. Our goal is to increase the chemical reactivity of the inert diamond surface and probe new routes for functionalization. We confirm the FND surface moieties using overlapping spectroscopies based on laboratory (FTIR) and synchrotron based techniques (X-ray absorption and X-ray photoelectron spectroscopies). Near surface covalent bond formation (inner shell chemistry) of tertiary amines, borates and silica are then used as molecular anchors for further functionalization with stabilizing and bioactive moieties. We demonstrate staining efficiency of FNDs by targeting folate receptors in HeLa cells and patterned substrates on quartz. Our work is promising for both the fundamental surface science of diamond surfaces and their applied use in biosensing modalities based on the nitrogen vacancy center.

#### 2:45 PM BREAK

SESSION EP09.04: Doping and Surface I  
Session Chairs: Jocelyn Achard and Paul May  
Monday Afternoon, November 26, 2018  
Hynes, Level 2, Room 207

#### 3:15 PM \*EP09.04.01

##### **Recent Development on Heavily Phosphorus Doped N-Type Diamond Growth** Satoshi Koizumi; NIMS, Tsukuba, Japan.

Deep donor level created by phosphorus doping is a serious problem for the electronics applications of diamond desired to utilize superior material's nature of diamond for ultimate semiconducting device formation. Hopping conductivity dominates in heavily doped diamond effectively reduces resistivity of n-type diamond as well as p-type boron doping case. The heavily doped layer should work as an efficient carrier source when it is used as contact layer in device structure. We have developed novel CVD system to bring high efficiency of gas phase doping, and using the machine, we found the substrate off angles influences greatly to conductivity improvement of n-type diamond. The talk will introduce current status of phosphorus doping especially in heavily doping regime.

#### 3:45 PM EP09.04.02

**Investigation of Doped Epitaxial Layer Grown on Half Inch HPHT Substrate from New Diamond Technology** Anatoly Vikharev<sup>1</sup>, Mikhail Lobaev<sup>1</sup>, Aleksey Gorbachev<sup>1</sup>, Dmitry Radishev<sup>1</sup>, Vladimir Isaev<sup>1</sup>, Mikhail Drozdov<sup>1</sup>, Pavel Yunin<sup>1</sup>, Vladimir Shashkin<sup>1</sup> and Aleksandr Koliadin<sup>2</sup>; <sup>1</sup>Institute of Applied Physics RAS, Nizhny Novgorod, Russian Federation; <sup>2</sup>New Diamond Technology, Saint Petersburg, Russian Federation.

Synthetic diamond as an electronic material is receiving international attention due to the improvements in the growth by both chemical vapor deposition

(CVD) and high pressure high temperature (HPHT) techniques. Diamond offers significant advantages over other semiconductor materials due to its high electrical breakdown strength, high carrier mobilities, high thermal diffusivity, and other exceptional properties. Diamond semiconductor devices will likely impact applications in high power, high frequency, high temperature, and/or harsh or corrosive environments.

In this paper the results on the investigations of boron- and phosphorus-doped epitaxial layers grown on HPHT substrates from New Diamond Technology (NDT) are presented. Investigations were made on a 2.45 GHz CVD reactor designed for growth of delta layers inside the single-crystalline CVD diamond [1]. The substrates of type *Ila* (100) diamonds prepared by HPHT technique in cubic presses at New Diamond Technology with dimensions of 3.5x3.5x0.5 mm as well as half inch in diameter and thickness 0.5 mm were used. At experiments extreme care was taken to substrate preparation, quality and roughness. Using substrates with dimensions 3.5x3.5x0.5 mm for homoepitaxial growth, undoped CVD films with improved structural characteristics were obtained. Also boron-doped delta-layer growth was investigated. As the result of experiments successful producing of delta layers with thickness 1-2 nm, boron concentration  $10^{21} \text{ cm}^{-3}$  and an abrupt interface between highly doped and undoped layers on a sub-nanometer transition layer was performed. Substrate of half inch in diameter and thickness 0.5 mm was characterized by different methods before CVD growth. Using this substrate the epitaxial layers doped by boron and phosphorus were produced. The surface morphology and uniformity of boron and phosphorus incorporation in the grown films were investigated by atomic force microscopy and secondary ion mass spectrometry, respectively. Produced doped layers with conductivity of p- and n-types are highly desirable for the development of diamond-based electronic devices.

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#### 4:00 PM EP09.04.03

**Raman and Photoluminescence Characterization of Arsenic-Doped Diamond by Ion-Implantation** Kaiyue Wang<sup>1</sup>, Yufei Zhang<sup>2</sup>, Huijun Wang<sup>2</sup> and Hong-Xing Wang<sup>1</sup>; <sup>1</sup>Xi'an Jiaotong University, Xian, China; <sup>2</sup>Taiyuan University of Science and Technology, Taiyuan, China.

Due to its wide band gap, high thermal conductivity, high carrier mobility and high breakdown field, diamond has been attracting much interest as the potential material of high-frequency high-power electronic device[1-3]. The device requires a high concentration of acceptors or donors, which could be obtained by the methods of doping. There are a great number of works on the doping of diamond. For n-type diamond, the nitrogen is the most common observed donor impurity and usually exists in natural diamond[4]. However, the quite-deep donor level of 1.7 eV is formed between the intermediate of diamond forbidden band, which makes it useless for semiconductor devices at room temperature[5].

As the same group V elements, arsenic is the shallower doping and expected as a more promising substitutional donor candidates[6]. The theoretical works showed that the substitutional arsenic provides the shallower donating level than phosphorus, at 0.4 eV below the bottom of the conduction band [7,8]. Nevertheless, there is less common involvement of the arsenic related defects in diamond as far. In this work, the arsenic related defects of diamond were investigated by technology of low temperature photoluminescence, and some new results were presented and discussed. A slice of ultrapure colorless diamond was involved which was synthesized by MPCVD. The (100) surface orientation of the sample was implanted with arsenic ions at 300K, with an energy of 150keV and a dose of  $10^{14}$  ions  $\text{cm}^{-2}$ , and then annealed at temperatures of 400C, 800C and 1500C. The Photoluminescence examination was performed by Renishaw micro-Raman spectrometers fitted with Linkam liquid nitrogen cooled stages at an excitation wavelength of 532 nm.

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#### 4:15 PM EP09.04.04

**Application of Laser-Induce Doping to Singlecrystalline Diamond** Abdelrahman Z. Ahmed<sup>3</sup>, Eslam Abubakr<sup>3</sup>, Yuki Katamune<sup>2</sup>, Shinya Ohmagari<sup>1</sup> and Tsuyoshi Yoshitake<sup>3</sup>; <sup>1</sup>Advanced Power Electronics Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Osaka, Japan; <sup>2</sup>Frontier Research Academy for Young Researchers, Kyushu Institute of Technology, Fukuoka, Japan; <sup>3</sup>Department of Applied Science for Electronics and Materials, Kyushu University, Fukuoka, Japan.

Diamond is a wide bandgap material with extreme thermal, electrical and optical properties that receives unprecedented attention since it is expected to handle more power with higher efficiency than conventional semiconductors. However, due to the intrinsic difficulties, device fabrication has serious problems in achieving n-type doping under good conditions. Moreover, diamond is not easily modified like other semiconducting materials that can be treated thermally after deposition.

Recently laser-induced doping has been applied to other wide band gap semiconductor (SiC) and its effectivity is experimentally proved. In this work, we applied laser-induced doping to singlecrystalline diamond, for the first time to our knowledge. The doping of phosphorus and Boron into singlecrystalline diamond is discussed from the chemical compositionally and electrically viewpoints.

In this work, Singlecrystalline diamond (100) plate (1b) was immersed in a phosphoric acid solution (85%) and Boric Acid. ArF excimer laser (Gigaphoton Inc. wavelength: 193 nm) beams were irradiated on it. The laser beam irradiation was carried out at a frequency of 1 Hz and at different laser fluences up to 3.9 J/cm<sup>2</sup>.

The results indicate that SC diamond hardly damaged on the plate surface by optical images even at a maximum fluence of 3.9 J/cm<sup>2</sup>. Electrically, the electrical conductivity increases with increasing fluence and number of laser shots. Moreover, Phosphorus depth profile was investigated by Secondary-Ion Mass Spectrometry (SIMS), in which the Incorporation of Phosphorus up to 30 nm was achieved by increasing number of shots and reducing time interval between successive shots.

Further systematic experiments are conducted, such as Raman, I-V measurements, and theoretical simulations, results will be reported at the conference.

This study was partially supported by JSPS KAKENHI Grant Numbers: JP15H04127, JP16K14391, and JSPS Fellow Grant JP17F17380.

#### 4:30 PM EP09.04.05

**Doping Level Determination of HPHT Diamond Substrate Using Electron Beam Induced Current** Cedric Masante<sup>1</sup>, Fabrice Donatini<sup>1</sup>, Nicolas Rouger<sup>2</sup> and Julien Pernot<sup>1</sup>; <sup>1</sup>University Grenoble Alpes, CNRS, Grenoble INP, Inst. NEEL, Grenoble, France; <sup>2</sup>Université de Toulouse; LAPLACE; CNRS; INPT; UPS, Toulouse, France.

For diamond power electronic applications, such as transistors and diodes, substrate quality is a key factor to obtain the best performances, influencing the properties of the epilayers. Moreover, understanding the properties of the substrate, especially doping level, is often necessary to design the devices accordingly.

In this work, Electron Beam Induced Current (EBIC) technique is used to visualize the lateral expansion of the depletion region of a Schottky contact

(Ti/Pt/Au stack) deposited on a (100) HPHT high quality substrate provided by New Diamond Technology. A comparison with finite element simulation has been performed in order to quantify key parameters. This method, requiring a single lithography process, is demonstrated to be efficient to extract doping levels below  $10^{16} \text{ cm}^{-3}$ , whereas SIMS measurements are only efficient for doping levels higher than this value. This method will be compared to previous measurements done by cathodoluminescence. The example presented in this work is a substrate having a p-type (Boron) doping level evaluated around  $3 \cdot 10^{15} \text{ cm}^{-3}$  near the surface (up to a few micrometers away from the surface). Diffusion lengths of a few micrometers are extracted and compared with recent measurements done on boron doped epilayers [2]. This method will also be applied to Nitrogen compensated substrates as a mean to test their electrical activity, prior to their use for devices.

#### References

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#### 4:45 PM EP09.04.06

**High Efficiency Doping of Boron Implanted (001) Diamond by High Temperature Annealing** Akinori Seki<sup>1</sup>, Taisuke Kageura<sup>2</sup>, Atsushi Hiraiwa<sup>2,3</sup> and Hiroshi Kawarada<sup>2</sup>; <sup>1</sup>Toyota Motor Corporation, Shizuoka, Japan; <sup>2</sup>Waseda University, Tokyo, Japan; <sup>3</sup>Nagoya University, Nagoya, Japan.

Diamond has excellent electrical characteristics as a wide gap semiconductor, and is expected as a high-performance power semiconductor for various applications as electric vehicles and trains etc.. Boron doping by ion-implantation has been applied to achieve low resistivity of p-type diamond [1, 2]. Tsubouchi reported that doping efficiency of about 50 % was achieved by annealing at 1600 °C after Boron implantation at 400 °C [2]. However, the doping efficiency is still not enough. Therefore, we propose a high-temperature annealing over 1600 °C by protecting the surface of diamonds as the effective recovering of implantation damage to achieve a high doping efficiency and crystallinity.

Boron was implanted at 500 °C by several accelerating voltages to form homogeneous Boron distribution profile in (001) diamond made by micro-wave plasma CVD. The density and the thickness of implantation layer were  $5 \times 10^{19} \text{ cm}^{-3}$  and 400 nm, respectively. To protect the surface of diamond, diamond-like carbon with 80 nm thickness was deposited on a surface of implanted diamond by plasma CVD. Post-annealing of Boron implanted diamond was carried out in Argon atmosphere at a range from 1500 to 1850 °C. The surface morphology was evaluated by optical microscope. The damage of implantation was evaluated by Rutherford backscattering (RBS).

The annealing for 10 minutes at 1850 °C was performed without degrading the surface morphology. It was clearly demonstrated that implantation damage can be reduced due to increase the temperature and the duration of annealing. Minimum channeling yield of the diamond annealed at 1500 °C for 60 minutes estimated by RBS was 6.6 %, and of the diamond annealed at 1800 °C for 30 minutes was 4.6 %, which is one of the lowest value after high dose boron implantation into diamond. Compared with annealing condition at 1500 °C, of that annealed at 1800 °C decreased almost by half. It indicates that the damage of implantation was fully recovered and almost the same as the un-implanted diamond without damage was obtained. At the same sample, the electrical resistivity measured by van der Pauw method was  $64 \Omega \text{ cm}$ , and high doping efficiency over 90 % was also obtained in heavily Boron doped diamond layer. The high dose implantation can be applicable to form source and drain region by self-alignment process.

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SESSION EP09.05: Quantum Effects  
Session Chairs: Julien Pernot and Emmanuel Scorsone  
Tuesday Morning, November 27, 2018  
Hynes, Level 2, Room 207

#### 8:30 AM \*EP09.05.01

**Diamond Nanosensors—Applications in Scanning Probe Microscopy** Christian Degen; ETH Zurich, Zurich, Switzerland.

Diamond has emerged as a unique material for a variety of applications, both because it is very robust and because it has defects with interesting properties. Our group is exploring diamond as a platform for realizing nanoscale sensors with exquisite sensitivities and new capabilities.

I will give an overview of the different sensor efforts pursued in our group, including nanomechanical resonators with high force sensitivities, ultrasharp diamond tips for non-contact force microscopy, and scanning tips for NV magnetometry applications.

#### 9:00 AM EP09.05.02

**Single Spin Magnetometry of Mesoscopic Superconductors at Cryogenic Temperatures** Lucas Thiel; Physics, Uni Basel, Basel, Switzerland.

Advancing the frontiers of nanoscience and information technology hinges on the availability of novel tools for nanoscale sensing and imaging. Solid state, electronic spins offer a unique platform to implement robust, high-performance quantum sensing devices, which go beyond what classical technologies can offer. The Quantum Sensing Group at Basel University has developed this idea into a robust technology based on nano-engineered diamond devices, which host single electronic spins for sensing.

In this talk, I will describe the key principles underlying these novel quantum sensors and demonstrate their application to nanoscale imaging in cryogenic environments, which we have pioneered in the last years. Specifically, I will focus on applications of single spin magnetometry to nanoscale studies of superconductors, where we were able to image stray fields of individual vortices with highest spatial resolution and more recently focussed on nanoscale studies of Meissner-effects in superconductor nanostructures. These experiments enable the local determination of fundamental materials properties, such as the London penetration depth, allow for the inspection of nanoscale defects inhibiting superconductivity and allow for benchmarking competing, microscopic models for supercurrent flow under various experimental conditions. These results establish scanning single spin magnetometry as a powerful tool for applications in solid-state, mesoscopic physics and the nano-sciences in general and offer unprecedented insights into the nanoscale properties of superconductors.

#### 9:15 AM EP09.05.03

**Quantum Electric-Field Imaging of Diamond Devices Using Nitrogen-Vacancy Centers** Kwangsoo Kim<sup>1</sup>, Kosuke Mizuno<sup>1</sup>, Toshiharu Makino<sup>2</sup>, Hiromitsu Kato<sup>2</sup>, Masahiko Ogura<sup>2</sup>, Daisuke Tekeuchi<sup>2</sup>, Satoshi Yamasaki<sup>2</sup>, Mutsuko Hatano<sup>1</sup> and Takayuki Iwasaki<sup>1</sup>; <sup>1</sup>Tokyo Institute of Technology,

Tokyo, Japan; <sup>2</sup>National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan.

Diamond semiconductor is a promising material for the next generation low-loss and compact power electronics due to its high breakdown field of 10 MV/cm and high thermal conductivity of 20 W/cmK. However, the number of previous reports on the high breakdown fields have been limited [1-2]. To understand the behavior of diamond devices and achieve the reliable devices possessing the high breakdown field, it is essential to monitor the internal electric-field in operating devices. So far, we have reported direct measurements of the internal electric-field in diamond devices using single nitrogen-vacancy (NV) centers [3]. However, the measurements were limited to spots, and thus, there was the difficulty in imaging the distribution of the electric-fields. In this study, we demonstrate the wide-field imaging of the electric-field inside a diamond device by utilizing a CCD camera and an ensemble of NV centers.

The NV centers were fabricated by ion implantation and subsequent annealing in vertical p-i-n diodes on a (111) p-type diamond substrate. For the electric-field imaging, an expanded laser beam (approximately 25  $\mu\text{m}$ ) was focused on a device in reverse-biased, and the fluorescence from the NV centers was detected by an electron multiplying CCD (EMCCD) camera with high spatial resolution (410 nm per pixel).

Optically detected magnetic resonance (ODMR) spectra were imaged in an area of 150  $\mu\text{m}^2$  in the device while applying a reverse bias of 400 V. The width between the ODMR dips increased upon the bias application due to the Stark effect of the NV centers [4]. We also observed several dips in the spectra, corresponding to different NV axes. The highest electric-field of approximately 1.4 MV/cm was obtained at the edge of the patterned n<sup>+</sup>-cathode, in agreement with three-dimensional device simulation. We confirmed that the electric-field decreased as the position was far away from the n<sup>+</sup>-cathode, and became 0.3 MV/cm at 2  $\mu\text{m}$  from the cathode. Accordingly, these facts indicate that two-dimensional distribution of the internal electric field in the device can be measured by using the NV centers. This technique will lead to the deep understanding and reliable devices.

Acknowledgements: This work was partially supported by KAKENHI (18H01472) and JST-CREST (Grant Number: JPMJCR1333)

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### 9:30 AM EP09.05.04

#### **Continuous-Wave Double Resonance of Electric Spin Triplet of NV Centers in Diamond and Its Application to High-Frequency AC Magnetic Field Sensing** Junko Ishi-Hayase<sup>1</sup>, Soya Saijo<sup>1</sup>, Tatsuma Yamaguchi<sup>1</sup>, Yuichiro Matsuzaki<sup>2</sup>, Shiro Saito<sup>2</sup>, Hideyuki Watanabe<sup>3</sup> and Norikazu

Mizuochi<sup>4</sup>; <sup>1</sup>Keio University, Yokohama, Japan; <sup>2</sup>NTT Basic Research Laboratories, Atsugi, Japan; <sup>3</sup>National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan; <sup>4</sup>Kyoto University, Uji, Japan.

Nitrogen-vacancy (NV) centers in diamond have received much attentions as highly-sensitive quantum sensors for detecting magnetic fields at room temperature. Pulsed optically detected magnetic resonance (ODMR) is typically used to detect AC magnetic fields, but can only be implemented after careful calibration that involves measuring continuous-wave (CW) ODMR, determining the Rabi frequency, and setting the microwave phase. In contrast, CW-ODMR can be simply implemented by continuous application of a green CW laser and a microwave field. However, CW-ODMR can be used to detect DC or low-frequency (kHz-range) AC magnetic fields. In this work, we report a method that uses NV centers and CW-ODMR to detect high-frequency (MHz-range) AC magnetic fields[1].

The proposed method involves a double resonance excitation of three level system of electric spin triplet states of NV centers. Unlike conventional methods, the proposed method does not require a pulse sequence; this greatly simplifies the procedure and apparatus needed for implementation. In the experiment, we applied continuous green laser, microwave (~2.8 GHz), and radio wave (~4 MHz) to NV center ensemble created by CVD growth and He ion implantation. We clearly observed the change in CW-ODMR spectrum with and without radio wave (~4 MHz), which is in good agreement with the theoretical calculation. This result demonstrates to detect AC magnetic field with high frequency (~MHz) by measuring CW-ODMR spectrum. The estimated sensitivity is to be of the order of  $\mu\text{T}/\text{Hz}^{1/2}$  for our present experimental apparatus. The sensitivity is currently limited by inhomogeneous broadening and low measurement contrast of samples used and by the low collection efficiency of the optical setup, both of which could be improved in the future. Thus, this simple alternative to existing AC magnetic field sensors paves the way for the development of a practical and feasible quantum sensor. Furthermore, we measured the intensity and frequency dependence of CW-ODMR spectra by applying MHz-radio wave. We found that the CW-ODMR spectra are significantly modulated due to the double resonance excitation by GHz-microwave and MHz-radio wave. We will discuss the involved physics by analyzing double resonance spectra of NV centers in detail.

This work was supported by JSPS KAKENHI (Grant No. 15K17732) and MEXT KAKENHI (Grants No. 18H01502, 15H05868, 15H05870, 15H03996, 26220602, and 26249108), and Spin-NRJ.

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### 9:45 AM EP09.05.05

#### **Investigation of Tin Vacancy Centers in Diamond for Realization of Spin-Photon Interfaces** Johannes Goerlitz<sup>1</sup>, Morgane Gandil<sup>1</sup>, Dennis Herrmann<sup>1</sup>, Philipp Fuchs<sup>1</sup>, Takayuki Iwasaki<sup>2</sup>, Takashi Taniguchi<sup>3</sup>, Mutsuko Hatano<sup>2</sup> and Christoph Becher<sup>1</sup>; <sup>1</sup>Saarland University, Saarbruecken, Germany; <sup>2</sup>Tokyo Institute of Technology, Tokyo, Japan; <sup>3</sup>National Institute for Materials Science, Tsukuba, Japan.

Color centers in diamond have received large recent attention as versatile tools for solid-state-based quantum technologies such as quantum information processing and quantum-enhanced sensing and metrology. They provide individually addressable spins with very long coherence times, narrow optical spectra and bright single-photon emission. In this context, impurity-vacancy color centers based on group-IV elements (SiV, GeV, SnV, PbV) have emerged as interesting systems promising to combine all desired favorable properties.

As a prime example, the negatively charged SiV center in diamond features an advantageous electronic structure and superior spectral properties [1]: At liquid helium temperatures, the SiV exhibits a narrow zero phonon line (ZPL) with a four-line fine structure and lifetime-limited linewidths on the order of 120MHz [2]. In addition, due to its small Huang-Rhys factor, up to 80% of the fluorescence is emitted via the ZPL. Moreover, the SiV offers an optically accessible  $\Lambda$ -type level structure with a large orbital level splitting allowing for fast all-optical control of its orbital [3] and spin [4] states. However, as a tradeoff, the SiV reaches millisecond spin coherence times only at millikelvin temperatures due to phonon-driven decoherence processes [4,5].

Motivated by these results there have been ongoing efforts to find a color center in diamond with both excellent optical properties (i.e. optically accessible  $\Lambda$ -level scheme) and long spin coherence times even at elevated temperatures (at least liquid Helium temperatures, i.e. 4K). Thus the heavier homologues of the SiV should be interesting candidates, because their orbital level splitting is considerably larger, thereby reducing phonon-induced decoherence processes. A very promising candidate is the tin vacancy center (SnV) emitting at 619nm and indeed showing a similar fine structure as the SiV center, but with a much larger ground and excited state splitting (850GHz and 3000GHz, respectively) [6].

Here, we present recent results on spectroscopy of both SnV ensembles and single SnV centers in high quality bulk diamond, from room temperature down

to liquid helium temperature. We find bright single photon emission from individual SnV centers from unstructured bulk material with saturation count rates up to 100,000 counts/second. We further explore their optical and spin properties, including lifetime, polarization, spectral features from photoluminescence and photoluminescence excitation, as well as spin coherence times, paving the way for assessing the suitability of the SnV center in diamond for spin-based photonic quantum technologies.

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**10:00 AM BREAK**

**10:30 AM EP09.05.06**

**Effective Regulation of NV-Centers Ensembles in Synthetic Diamond** Yang Shen, Licai Hao, Shulin Gu, Rong Zhang and Youdou Zheng; Nanjing University, Nanjing, China.

Solid-state quantum emitters embedded in a semiconductor crystal environment are potentially scalable platforms for quantum optical networks operated at room temperature. Prominent representatives are nitrogen-vacancy (NV) centers in diamond showing coherent entanglement and interference with each other. However, a remaining challenge is how to regulate NV centers efficiently. Here, we demonstrate that the implementation of nitrogen, oxygen or sulfur into  $H_2/CH_4$  plasma to tailor the intensity of NV centers. Higher crystal quality of epitaxial films is first confirmed by comparing the FWHM of the diamond first-order Raman peak with the HPHT diamond substrate. By the engineering of nitrogen flow into the plasma, we find that the intensity of NV centers increases with the flow of nitrogen simultaneously, and the growth rate of epitaxial films first increases and then tends to be stable, while the intensity of NV centers decreases with the flow of sulfur and the growth rate of epitaxial films also keeps decreasing. However, the intensity of NV centers and growth rate show different trends when oxygen is added into the  $H_2/CH_4$  plasma. The regulation of oxygen on the NV centers is first promoted and then suppressed. Only when the flow of oxygen is less than 0.4% ( $H_2+CH_4$ ), oxygen promotes the intensity of NV centers. Due to the competition mechanism of oxygen and nitrogen in  $H_2/CH_4$  plasma, the growth rate decreases with the increasing flow of oxygen, and finally tends to zero when the flow of oxygen reaches 1% ( $H_2+CH_4$ ). Our study demonstrates NV centers as an adjustable defect for quantum photonics architecture relying on single photon source and qubits.

**10:45 AM EP09.05.07**

**High-Sensitive Vector Magnetic Field Sensing by Simultaneous Control of Spin State of NV Center Ensemble in Diamond Using Multi-Frequency Microwaves** Ken Yahata<sup>1</sup>, Yuichiro Matsuzaki<sup>2</sup>, Kosuke Kakuyanagi<sup>2</sup>, Shiro Saito<sup>2</sup>, Hideyuki Watanabe<sup>3</sup> and Junko Ishi-Hayase<sup>1</sup>; <sup>1</sup>Keio University, Yokohama, Japan; <sup>2</sup>NTT Basic Research Laboratories, Atsugi, Japan; <sup>3</sup>National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan.

Nitrogen-vacancy center in diamond (NV center) is a promising candidate for highly-sensitive nano-scale magnetic field sensor, because its spin state has a long coherence time and can be initialized, manipulated, and detected by irradiating light and/or microwave at room temperature. Moreover, vector magnetic field can be estimated by measuring an ensemble of NV center with four different orientation axes, because the energy shift of the spin state with each axis is approximately proportional to the magnetic-field vector component along the axis. However, in the conventional scheme, it has been an essential obstacle that low signal from NV centers with the target axis and noise from NV centers with the other axes decrease the sensitivity. For this reason, in the previous research, methods such as raising the sensitivity by utilizing the hyper-fine structure with nitrogen nuclear spin or reducing measurement time by multi-frequency microwaves control are taken. In this work, we propose and demonstrate a new scheme that improves the sensitivity of the vector magnetic field sensing by synthesizing signal from NV centers with four axes where the spin state with each axis is simultaneously manipulated by simultaneously applying microwaves with four different frequencies.

In our scheme for multi-frequency vector magnetic field sensing, the sensitivity can be improved by synthesizing signals from each orientation axis using a special microwave pulse train with four frequencies. At this time, the direction of the spin with a specific orientation axis is reversed by changing the phase of an arbitrary one or two frequency microwave pulses. By changing the spin reversal orientation according to the direction of the magnetic field, it is possible to improve the sensitivity to magnetic fields in all directions. Moreover, by changing the two frequencies of spin reversal, the x, y and z components of the magnetic field can be measured directly. The most important advantage of our scheme is that the sensitivity can be improved for regardless of NV center sample orientation and pulse measurement methods.

By our theoretical calculation, we showed the sensitivity of our scheme can be improved 2~4 times better than the sensitivity of conventional scheme[1]. In the experimental demonstration, we confirm the sensitivity of our scheme becomes 2 times better than the sensitivity of conventional scheme. Moreover, we demonstrate a vector magnetic field sensing using our scheme with higher sensitivity using confocal and wide-field experiment system. Our scheme can be applied to various type of pulse sequences for magnetic field sensing and enables us to improve the sensitivity by simultaneous manipulation of spin states with four orientation axes.

This work was supported by JSPS KAKENHI (Grant No. 15K17732) and MEXT KAKENHI (Grants No. 18H01502, 15H05868, 15H05870, 15H03996, 26220602, and 26249108[HJ4]), and Spin-NRJ.

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**11:00 AM EP09.05.08**

**First-Principles Investigation of Nitrogen Vacancy Center in Diamond (113) Surface** Song Li<sup>1</sup>, Jyh-Pin Chou<sup>1</sup>, Jie Wei<sup>1</sup>, Minglei Sun<sup>2</sup>, Alice Hu<sup>1</sup> and Adam Gali<sup>3</sup>; <sup>1</sup>City University of Hong Kong, Kowloon Tong, Hong Kong; <sup>2</sup>School of Mechanical Engineering, Southeast University, Nanjing, China; <sup>3</sup>Wigner Research Centre for Physics, Budapest, Hungary.

The nitrogen vacancy (NV) center in diamond demonstrates promising future in quantum simulator and sensor applications. Nevertheless the shallow NV center under surface could be significantly influenced by surface termination and thus limit its sensitivity. The first-principles calculations have been performed on (113)-orientated slabs of diamond to investigate ideal surface termination for hosting NV center. We considered hydrogen, oxygen, fluorine, hydroxyl, nitrogen, and mixed terminations. Results show that different chemical termination of diamond could significantly change its electronic and chemical properties. Fluorine and oxygen terminations on diamond (113) surface could eliminate surface states intrusion in deep bandgap thus stabilize the fluorescent state of negatively charged NV. Moreover the oxygen terminated (113) diamond surface could form ordered and smooth surface thereby avoid surface spin caused by surface fluctuation. The stability calculation indicates it may achieve oxygen termination on (113) diamond surface during conventional diamond CVD growth condition.

**11:15 AM \*EP09.05.09**

**Progress and Challenges of NV-Doped Diamond for Ultrasensitive Laser Threshold Magnetometry** Jan Jeske<sup>1,2</sup>, Verena Zuerbig<sup>1</sup>, Lutz Kirste<sup>1</sup>, Sarath Raman Nair<sup>3</sup>, Xavier Vidal<sup>4</sup>, Lachlan J. Rogers<sup>3</sup>, Thomas Volz<sup>3</sup>, Ondrej Kitzler<sup>4</sup>, Richard P. Mildren<sup>4</sup>, Shinobu Onoda<sup>5</sup>, Takeshi Ohshima<sup>5</sup>, Fedor Jelezko<sup>6</sup>, Philipp Reineck<sup>7</sup>, Marco Capelli<sup>7</sup>, Desmond W. Lau<sup>7</sup>, Jared Cole<sup>2</sup>, Brant Gibson<sup>7</sup> and Andrew Greentree<sup>7</sup>; <sup>1</sup>Fraunhofer IAF, Freiburg, Germany; <sup>2</sup>Chemical and Quantum Physics, School of Science, RMIT University, Melbourne, Victoria, Australia; <sup>3</sup>ARC CoE for EQuS, Department of Physics and Astronomy, Macquarie University, Sydney, New South Wales, Australia; <sup>4</sup>Department of Physics and Astronomy, Macquarie University, Sydney, New South Wales, Australia; <sup>5</sup>National Institute for Quantum and Radiological Science and Technology, Takasaki, Japan; <sup>6</sup>Institute for Quantum Optics / IQST, Universität Ulm, Ulm, Germany; <sup>7</sup>ARC CoE for Nanoscale BioPhotonics, RMIT University, Melbourne, Victoria, Australia.

Nitrogen-vacancy centres in diamond are being widely employed to measure magnetic fields. We performed theoretical calculations showing that the precision of NV magnetometry can be vastly improved by using diamond material with high NV densities as a laser medium and making use of the intrinsic amplification and high collection efficiency of a laser system. In this way quantum-limited sensitivities could become competitive with ultra-sensitive SQUID sensors.

Motivated by this result we investigated experimentally the properties of stimulated emission of NV centre ensembles in diamond. Combining green (532nm) pump light with red (~700nm) stimulating light, we measured spontaneous and stimulated emission and characterised the occurrence of induced absorption channels.

Placing NV diamonds in optical cavities we measured an amplification of red light transmitted through the cavity, when a green pump laser was added, by a factor of 3. We furthermore identified material properties and improvement challenges and strategies for CVD growth of diamond tailored to the realisation of an NV centre laser and laser threshold magnetometry.

SESSION EP09.06: FET Devices I  
Session Chairs: Hiroshi Kawarada and David Moran  
Tuesday Afternoon, November 27, 2018  
Hynes, Level 2, Room 207

#### 1:45 PM EP09.06.01

**The Interface Properties of Al<sub>2</sub>O<sub>3</sub>/NO<sub>2</sub>/H-Diamond in MOSFET Structure Studied by Capacitance and Conductance and Synchrotron XPS/XANES Measurements** Niloy C. Saha<sup>1</sup>, Kazutoshi Takahashi<sup>2</sup>, Satoshi Masuya<sup>1</sup>, Masaki Imamura<sup>2</sup> and Makoto Kasu<sup>1</sup>; <sup>1</sup>Electrical and Electronic Engineering, Saga University, Saga, Japan; <sup>2</sup>Synchrotron Light Application Center, Saga University, Saga, Japan.

Diamond with a wide band-gap of 5.47 eV and high break-down field of >10 MV/cm is expected to be best semiconductor material for high-power and high-frequency transistors. Diamond field effect transistor (FET) exhibited high RF output power density of 2 W/mm at 1 GHz, transition frequency ( $f_T$ ) of 45 GHz and the cut-off frequency of power gain ( $f_{MAX}$ ) of 120 GHz. Inorganic gases, such as O<sub>3</sub>, NO<sub>2</sub>, NO, and SO<sub>2</sub> adsorbed on H-diamond surface and generate hole carriers. This phenomenon can be explained as the inorganic molecule accommodate electrons and induce holes due to the lower molecular orbital energy of these gases than diamond valence band maximum (VBM) [1]. The NO<sub>2</sub> p-type doping increases hole sheet concentration up to  $\sim 1 \times 10^{14} \text{ cm}^{-2}$ . Recently, M. Geis et. al. reported that presence of NO<sub>3</sub><sup>-</sup> peak on NO<sub>2</sub>-adsorbed H-diamond [2]. For FET, we have been using NO<sub>2</sub> p-type doping in H-diamond. However, Al<sub>2</sub>O<sub>3</sub>/NO<sub>2</sub>/H-diamond interface structure is yet to be identified more clearly. Al<sub>2</sub>O<sub>3</sub>/NO<sub>2</sub>/H-C, Al<sub>2</sub>O<sub>3</sub>/NO/H-C, and Al<sub>2</sub>O<sub>3</sub>/SO<sub>2</sub>/H-C structures were investigated by XPS/XANES measurements, where valence band offsets were determined to be 3.9, 3.7 and 3.5 eV, respectively, suggesting decomposition of exposed gases. Oxygen-derived interface state was detected but No N or S peak was found at the interface.

In the C-V measurements, the flat-band voltage of Al<sub>2</sub>O<sub>3</sub>/NO<sub>2</sub>/H-C MOS structures shifted towards positive voltage side by 2 V compared to that of Al<sub>2</sub>O<sub>3</sub>/H-C MOS. We also found that exposure of inorganic gases reduces the work function of H-diamond surface and shifted flat-band voltage towards the positive side. Interfacial properties were measured using conductance method by measuring parallel conductance from 1 kHz – 1 MHz. By fitting the parallel conductance, we separated border trap density in Al<sub>2</sub>O<sub>3</sub> layer and interface state density. values are  $\sim 5.7 \times 10^{12}$  and  $\sim 4.8 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$  respectively for the Al<sub>2</sub>O<sub>3</sub>/NO<sub>2</sub>/H-C and Al<sub>2</sub>O<sub>3</sub>/H-C MOS structures at room temperature.

In conclusion, we have identified oxygen-state at the interface of Al<sub>2</sub>O<sub>3</sub>/NO<sub>2</sub>/H-C structure using XPS/XANES measurements which is also confirmed by measuring conductance and compared to that of Al<sub>2</sub>O<sub>3</sub>/H-C structure. This investigation provides the information that NO<sub>2</sub> exposure does not incorporate directly into interfacial states as the values in both cases are within the same range. A comprehensive demonstration will be discussed.

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#### 2:00 PM EP09.06.02

**Vertical-Type 2DHG Diamond MOSFETs Over 5000 A/cm<sup>2</sup> and Low On-Resistance 6 mΩcm<sup>2</sup>** Masayuki Iwataki<sup>1</sup>, Nobutaka Oi<sup>1</sup>, Kiyotaka Horikawa<sup>1</sup>, Shotaro Amano<sup>1</sup>, Taisuke Kageura<sup>1</sup>, Masafumi Inaba<sup>2</sup>, Atsushi Hiraiwa<sup>2,1</sup> and Hiroshi Kawarada<sup>1,3</sup>; <sup>1</sup>Waseda University, Shinjuku, Japan; <sup>2</sup>Nagoya University, Nagoya, Japan; <sup>3</sup>Kagami Memorial Research Institute for Materials Science and Technology, Shinjuku, Japan.

We have reported excellent characteristics of high breakdown voltage and stable operation in wide temperature range in 2 dimensional hole gas (2DHG) diamond metal-oxide-semiconductor field effect transistor (MOSFET) with Al<sub>2</sub>O<sub>3</sub> gate insulator and passivation film by high temperature atomic layer deposition (ALD) method [1][2]. 2DHG is preserved by ALD-Al<sub>2</sub>O<sub>3</sub> near the interface of hydrogen terminated diamond [3][4]. The 2DHG is induced independent on crystal orientation. So, the trench side wall is used for drift region [5]. We have also reported vertical-type 2DHG Diamond MOSFET with trench structure [5] and obtained high current density and on/off ratio by forming the nitrogen doped layer as a block layer [6]. For vertical GaN devices, high current density over 2000 A/cm<sup>2</sup> and low on-resistance of 1.8 mΩcm<sup>2</sup> have been reported [7]. The same level performance is also required for vertical diamond devices. In this work, we further miniaturized vertical-type 2DHG Diamond MOSFET with trench opening length 2 or 4 μm and incorporated overhanging gate electrode structure on the source electrode for improvement of on-current density.

The fabrication process is follows. First, the 2 μm nitrogen doped layer is grown to suppress leakage current on the boron doped layer by microwave plasma chemical vapor deposition method. The nitrogen concentration is changed stepwise from  $2.0 \times 10^{18} \sim 8.0 \times 10^{18} \text{ cm}^{-3}$  in order to assuage the electric field overconcentration. The trench is formed by Inductive Coupled Plasma Reactive Ion Etching. The trench opening length is 2 or 4 μm and the depth is 3 ~ 4 μm. After forming the trench, undoped layer (200 nm) is grown epitaxially again to induce the 2DHG layer. 200 nm Al<sub>2</sub>O<sub>3</sub> is deposited high

temperature ALD method. The gate length is 2  $\mu\text{m}$  and part of the gate electrode has an overhanging structure which is liable to be placed on the source electrode. So, the length between source and gate electrode is 0  $\mu\text{m}$  and also the device size itself is miniaturized. We defined the device active area is calculated the length of between both source electrodes (6 ~ 16  $\mu\text{m}$ ) and the channel width (25  $\mu\text{m}$ ). The drain current density is -200 mA/mm at  $V_{\text{DS}}$  of -50 V and  $V_{\text{GS}}$  of -20 V. In the active area  $1.5 \times 10^{-6} \text{ cm}^2$  device, the maximum drain current which is normalized with respect to active area is -6000 A/cm<sup>2</sup> at  $V_{\text{DS}}$  of -50 V and  $V_{\text{GS}}$  of -20 V and the specific on-resistance is 5.8 m $\Omega\text{cm}^2$ . The on/off ratio is 10<sup>8</sup>. Specific on-resistance and normalized current density are much more improved by the miniaturization of device area.

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### 2:15 PM EP09.06.03

**Normally-Off 2DHG Diamond Al<sub>2</sub>O<sub>3</sub>/SiO<sub>2</sub> MOSFETs without Deteriorating Drain Current Density** Taichi Yabe<sup>1</sup>, Nobutaka Oi<sup>1</sup>, Kiyotaka Horikawa<sup>1</sup>, Satoshi Okubo<sup>1</sup>, Jorge J. Buendia<sup>1</sup>, Taisuke Kageura<sup>1</sup>, Shozo Kono<sup>1</sup>, Atsushi Hiraiwa<sup>1</sup> and Hiroshi Kawarada<sup>1,2</sup>; <sup>1</sup>Waseda University, Shinjuku-ku, Japan; <sup>2</sup>Kagami Memorial Research Institute for Materials Science and Technology, Shinjuku-ku, Japan.

Diamond is expected to be the next generation of power device material as wide band gap semiconductor with special properties such as high thermal conductivity and high breakdown field. Hydrogen-terminated diamond MOSFETs with a reported high breakdown voltage characteristic [1] and stable operation in wide temperature range [2] have been reported in previous research. Diamond MOSFETs use Two-Dimensional Hole Gas (2DHG) which is induced by negative adsorbates or passivation film on hydrogen-terminated surface. In general, 2DHG diamond MOSFETs are normally-on since 2DHG channel is induced without gate bias. But power devices are required to be normally-off for safety. Normally-off diamond MOSFETs have already been reported for C-H diamond MOSFETs with partial C-O channel [1], HfO<sub>2</sub>-gated diamond MOSFETs [3] and inversion channel diamond MOSFETs. In this study, we demonstrate normally-off MOSFETs by the insertion of thin SiO<sub>2</sub> layer in diamond/Al<sub>2</sub>O<sub>3</sub> interface. SiO<sub>2</sub> which do not have negative charge is not induced 2DHG. So, normally-off is achieved by insertion of SiO<sub>2</sub> into MOS structure. In addition, we could suppress the deterioration of drain current density.

The fabrication process was as follows. Undoped homoepitaxial diamond layer was deposited on Ib (001) diamond substrates by Chemical Vapor Deposition, and electrodes were deposited as source and drain. 1<sup>st</sup> Al<sub>2</sub>O<sub>3</sub> film was deposited as gate passivation by high-temperature ALD [4] after hydrogen-termination. Al<sub>2</sub>O<sub>3</sub> is partially etched in the 20 % (2 $\mu\text{m}$ ) of channel area, where C-H surface is exposed in part. Si thin film (1nm) was deposited directly on the clean C-H surface at 723 K, and the Si film was fully oxidized by air and the subsequent 2<sup>nd</sup> Al<sub>2</sub>O<sub>3</sub> deposition. The 2<sup>nd</sup> Al<sub>2</sub>O<sub>3</sub> film was deposited as gate insulator by the same high-temperature ALD [4]. Finally, gate electrode was deposited form MOS structure where 20% of channel C-H surface is directly covered Al<sub>2</sub>O<sub>3</sub> without surface negative charge which cause 2DHG.

The gate threshold voltage ( $V_{\text{th}}$ ) of the device was -2.0 V which is suitable for power device application.  $V_{\text{th}}$  control and normally-off operation were achieved. The maximum drain current density was -67 mA/mm at  $V_{\text{DS}} = -50$  V when  $V_{\text{GS}}$  was -40 V. The size of device was  $L_{\text{SG}} = 2 \mu\text{m}$ ,  $L_{\text{G}} = 10 \mu\text{m}$  and  $L_{\text{GD}} = 2 \mu\text{m}$ . In addition, normally-off devices were achieved in various size. The size of device was  $L_{\text{SG}} = 2 \mu\text{m}$ ,  $L_{\text{G}} = 10 \mu\text{m}$ ,  $L_{\text{GD}} = 5$  and  $10 \mu\text{m}$ .  $V_{\text{th}}$  were -5.8 and -5.7 V. The maximum drain current density ( $V_{\text{DS}} = -50$  V,  $V_{\text{GS}} = -40$  V) were -52 and -53 mA/mm, which are larger other diamond normally off devices.

We fabricated 2DHG diamond Al<sub>2</sub>O<sub>3</sub>/SiO<sub>2</sub> MOSFETs and obtained normally-off operation without deteriorating of drain current density.

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### 2:30 PM EP09.06.04

**Increased Hole Accumulation at the H-Terminated Diamond / Al<sub>2</sub>O<sub>3</sub> Interface with V<sub>2</sub>O<sub>5</sub> as the Surface Dopant** Yichen Yao, Yu Yang, Xingye Wang, Franz A. Koeck and Robert J. Nemanich; Arizona State University, Tempe, Arizona, United States.

High-k oxides like Al<sub>2</sub>O<sub>3</sub> have been deposited on hydrogen terminated diamond surface as gate insulator and achieve a thermally stable passivation on the conducting diamond surface. The surface transfer doping induced by high electron affinity transition metal oxides like V<sub>2</sub>O<sub>5</sub> and MoO<sub>3</sub> has the potential to increase hole concentration at the H-diamond/dielectric interface. In this study we use plasma enhanced ALD to grow an ultra-thin Al<sub>2</sub>O<sub>3</sub> passivation layer on top of hydrogenated (100) diamond followed by a hydrogen plasma process at 500C to achieve a thermally stable passivation layer. XPS spectra have shown a large valence band difference of 3.5 eV after the hydrogen plasma treatment which we relate to both the valence band discontinuity and a dipole due to interface charge transfer. A simple capacitor model is used to estimate the change in hole concentration at the H-diamond surface. The addition of a V<sub>2</sub>O<sub>5</sub> layer results in a surface resistance of 4.5 kOhms/square. A hole concentration of  $2.70 \times 10^{13} \text{ cm}^{-2}$  and a mobility of 52 cm<sup>2</sup>/V-s have been determined from Hall measurements of the H-diamond/Al<sub>2</sub>O<sub>3</sub>/V<sub>2</sub>O<sub>5</sub> structure. We present a model of the interface charge distribution that could represent the measured band structure.

This research is supported by the NSF through grant DMR-1710551 and a grant from MIT-Lincoln Laboratory.

### 2:45 PM BREAK

SESSION EP09.07: Electron Emission and Electrochemistry  
Session Chairs: Makoto Kasu and Oliver Williams  
Tuesday Afternoon, November 27, 2018  
Hynes, Level 2, Room 207

### 3:15 PM \*EP09.07.01

**The Influence of Structural and Morphological Properties on the Electron Field Emission of CVD Diamond Films** Ken Haenen<sup>1,2</sup>; <sup>1</sup>Institute for Materials Research (IMO), Hasselt University, Diepenbeek, Belgium; <sup>2</sup>IMOME, IMEC vzw, Diepenbeek, Belgium.

Because of the unique surface properties of diamond, including the negative electron affinity when H-terminated, the material is considered an excellent candidate electron field emitter. However, to reach its full potential, exhibiting superior electron field emission, the problem of the low electrical conductivity of bulk diamond, due to its wide band gap, must be overcome.

Using polycrystalline diamond layers, composed of sp<sup>3</sup>-bonded diamond grains embedded in an amorphous / graphitic sp<sup>2</sup>-bonded carbon matrix forming the grain boundaries, a successful strategy to manipulate the conductivity of the material is to alter the microstructure of grains and grain boundaries. This can be done in several ways, including renucleation during growth, in-situ doping, and post-deposition ion implantation of several active elements. Several strategies will be discussed and compared. The observed electron emission currents will be correlated with structural information obtained by advanced transmission electron microscopy techniques. Electron field emission currents, including long-term stability and application in microplasma devices, underpin the observations. Finally, heterostructures of diamond with other novel materials such as hexagonal boron nitride, graphene, etc, will be considered in relation to their electron emission properties.

#### 3:45 PM EP09.07.02

**Diamond Electron Emission into Water** [Robert J. Hamers](#), Shuo Li and Jason Bandy; University of Wisconsin-Madison, Madison, Wisconsin, United States.

Diamond's unique chemical stability allows it to be used as an electron emitter under unusual conditions, including in water. However, the large bandgap of diamond makes it a poor absorber of light even at short wavelengths. The emission of electrons from diamond can be improved by creating novel types of heterojunctions with metals, with semiconductors, and by integrating metal nanoparticles directly into the diamond film. The incorporation of silver nanoparticles directly into diamond films confers significant changes in optical properties as well as changes in electron emission characteristics. We have evaluated the electron emission characteristics of diamond-based heterojunctions as a function of wavelength, diamond film thickness, and other variables in order to understand how to achieve the most effective electron emission. In this talk I will present recent data comparing photoelectron emission from diamond and diamond-based heterostructure devices, with the goal of facilitating the use of diamond as an electron emitter operating under ambient environments.

#### 4:00 PM EP09.07.03

**A Study of Negative Electron Affinity from Aluminium on the Diamond Surface** [Michael James](#), Paul W. May and Neil L. Allan; University of Bristol, Bristol, United Kingdom.

The ability to form a negative electron affinity (NEA) surface on diamond is of interest for electron emission applications. These surfaces form when atoms electropositive relative to carbon terminate the surface. Simple H-termination gives NEA but hydrogen desorption occurs at elevated temperatures (>700 °C).<sup>1</sup> This makes H-terminated diamond unsuitable for high-temperature applications.

Previous work has studied NEA surfaces generated by termination from group I, II and transition metals (TMs).<sup>2-4</sup> Larger group I metals do not have thermal stability but smaller group I and II metals, such as Li and Mg, show promise. Computational work on various first-row TMs including Cu, Ni, Ti and Zn, suggest carbide-forming TMs give larger NEA and experimental work has shown <10 Å thin films of various TMs can give NEA.

Density functional theory calculations simulate the addition of up to 1 ML of aluminium on the diamond surface. Aluminium is a carbide-forming metal that bonds sufficiently well to be used for Ohmic and Schottky contacts,<sup>5</sup> and here we show it is of interest for NEA applications as well. For certain Al coverages, for example 0.25 ML coverage on the (100) O-terminated surface, we find adsorption energies were observed to be larger than for H-termination whilst maintaining a NEA.

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#### 4:15 PM EP09.07.04

**The Electrochemical Reduction Mechanism of Hydrogen Peroxide on Silver Nanoparticles Modified Boron Doped Diamond Electrodes** [Xiaosheng Cai](#), Eden E. Tanner, Chuhong Lin, Kamonwad Ngamchuea, John S. Foord and Richard G. Compton; Department of Chemistry, University of Oxford, Oxford, United Kingdom.

The hydrogen peroxide reduction on boron doped diamond electrodes modified by silver nanoparticles in a neutral phosphate buffer solution shows a CE mechanism. A diffusion oxygen layer is formed firstly along with water via the disproportionation of hydrogen peroxide on silver nanoparticles, and then reduced to hydrogen peroxide during electrochemistry process. Cyclic voltammetry and simulation are combined to confirm the mechanism, demonstrating the electrochemical reduction signal depends on the interacting time between silver and hydrogen peroxide via the disproportionation step which occurs before the voltammetric analysis.

#### 4:30 PM EP09.07.05

**Theoretical Study on Termination Dependent Redox Reactivity of Boron-Doped Diamond / Water Interface** [Shota Iizuka](#)<sup>1</sup>, Keisuke Natsui<sup>2</sup>, Yasuaki Einaga<sup>2</sup> and Yoshitaka Tateyama<sup>1</sup>; <sup>1</sup>National Institute for Materials Science, Tsukuba, Japan; <sup>2</sup>Keio University, Yokohama, Japan.

Boron doped diamond (BDD) is a promising electrode material, which has wide potential window and low background current. Our experimental studies so far demonstrated that the electrochemical characteristics of BDD can be modified by different surface terminations. Recently, the electrochemical properties of hydrogen (H)-, hydroxyl (OH)-, and fluorine (F)-terminated BDD were compared with the cyclic voltammogram measurement of anionic, neutral and cationic redox targets [1]. It is then observed that the oxidation and reduction current densities decrease for F-BDD, compared to H- and OH-BDD. Especially, the current density for anionic target was significantly suppressed in the case of F-BDD. Also, the oxidation potential for each target monotonously shifted toward the positive direction.

To understand such differences in the electrochemical behavior, we calculated H-, OH-, and F-terminated BDD/water interfaces, employing Car-Parrinello molecular dynamics based on density functional theory.

In the calculated electronic structures of H-, OH-, and F-BDD/water interfaces, we found that valence band maximum (VBM) of H-BDD is located at

highest energy position, while F-BDD has much lower band position. For redox reactions with the targets, the Fermi level, nearly VBM, of p-type semiconductor BDD should coincide with the target redox potential according to the Fermi's golden rule. With the hypothesis of surface band-edge pinning, VBM in H-BDD does not need to go up from the open circuit condition, while that in F-BDD needs significant upward shift. This causes large downward band bending in the subsurface region of BDD, which plays a barrier role for the electron / hole tunneling between the BDD electrode and the redox target. This is not the case in H-BDD in fact, and the observed redox behaviors are roughly accounted for by this mechanism. For more comprehensive explanation, we also analyzed distribution of interfacial water on H-, OH-, and F-BDD/water interfaces, and the interfacial charge. Regarding H-BDD and F-BDD, oxygen atoms of water distributed farther from the BDD surface than OH-BDD. This suggests that H- and F-BDD surfaces are hydrophobic. This hydrophobicity increases the tunneling length of electron / hole between BDD and the target in water. We also found that F-BDD has more negative surface than the others, reflecting large electronegativity of fluorine atom. This indicates that it is difficult for anionic target to approach the BDD surface and the tunneling length becomes larger. Overall theoretical evidences well explain almost all the observations in the experiment. These fundamental properties obtained will give a useful insight into how the redox reaction occurs at the interface.

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#### 4:45 PM EP09.07.06

**New Electric Seawater Wireless Communication using Diamond Solution-Gate Field-Effect Transistors** Yutaro Iyama<sup>1</sup>, Miki Kazuya<sup>1</sup>, Kaito Tadenuma<sup>1</sup>, Shailli Falina<sup>1</sup>, Mohd Syamsul<sup>1</sup>, Yu Hao Chang<sup>1</sup>, Yukihiro Shintani<sup>1</sup> and Hiroshi Kawarada<sup>1,2</sup>; <sup>1</sup>Waseda University, Shinjuku-ku, Japan; <sup>2</sup>Kagami Memorial Research Institute for Materials Science and Technology, Shinjuku-ku, Japan.

We propose a new electric wireless communication under the sea water; it utilizes diamond solution-gate FETs (SGFETs) [1] where the semiconductor surface is directly immersed in solution (e.g. seawater), and drain current ( $I_{DS}$ ) is remotely controlled by electric signals ( $V_{GS}$ ) of a reference electrode.

Seawater wireless communication has been required for many purposes. The electromagnetic waves are heavily attenuated in the seawater due to highly ionized media [2]. In general, the acoustic waves and visible light are used for seawater communication. However, these seawater communication means are not appropriate for mobile seawater robots; the reasons are that acoustic waves induce transmission problems such as Doppler shifts, and that the visible light requires accurate alignment between a transmitter and a receiver [2]. On the other hand, electric signals have relatively low attenuation and isotropic distribution of electric field due to electrical conductivity of seawater. Thus, electric seawater wireless communication has potential for mobile seawater robots [3]. In this work, we mainly investigated two points; first, how far the electric signals are transmitted, and second, what the maximum operation frequency of SGFETs is in the vast sea.

This communication setup consisted of two components; a reference electrode as a transmitter and SGFET as a receiver. The reference electrode, which was remote from the SGFET, applied electric signals ( $V_{GS}$ ) via seawater. Then, the SGFET received the electric signals ( $V_{GS}$ ) via seawater. Also, each of the source potentials was common ground in order to obtain stable reference potential.  $I_{DS}$ - $V_{DS}$  and switching characteristics of the SGFETs were measured. Then, the distances between the reference electrode and the SGFET were increased gradually until reaching 10 m in a shallow sea shore in Tokyo Bay.

The electric signals ( $V_{GS}$ ) of the reference electrode propagated without attenuation in the sea. In both 1 and 10 m, ideal  $I_{DS}$ - $V_{DS}$  characteristics were obtained by electric signals ( $V_{GS}$ ). Moreover, the switching times for  $T_{ON}$  and  $T_{OFF}$  were both less than 1  $\mu$ s. Therefore, between 100 kHz-1 MHz, this setup was capable of communicating within 10 m in the sea. The limit of frequency governed by a long ground line. The operation frequency can be increased further by considering a new ground. The 10 m is not a limit of this wireless communication, but can be extended much more, because the signal does not differ from 1 m to 10 m.

We adopted diamond SGFETs to establish new electric seawater wireless communication. This communication method using SGFETs is applicable for mobile seawater robots because electric signals have relatively low attenuation and isotropic distribution of electric field.

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SESSION EP09.08/EP08.06: Joint Session I: Diamond Devices

Session Chairs: Etienne Gheeraert and Mark Hollis

Wednesday Morning, November 28, 2018

Hynes, Level 2, Room 207

#### 8:30 AM \*EP09.08.01/EP08.06.01

**Recent Progresses in Deep Depletion Diamond MOSFET** Cedric Masante<sup>1</sup>, Toan Thanh Pham<sup>1,2</sup>, Nicolas Rouger<sup>4</sup>, Gauthier Chicot<sup>1,2</sup>, Florin Udrea<sup>3</sup>, David Eon<sup>1</sup>, Etienne Gheeraert<sup>1</sup>, Daniel Araujo<sup>5</sup> and Julien Pernot<sup>1</sup>; <sup>1</sup>University Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France; <sup>2</sup>Univ. Grenoble Alpes, CNRS, Grenoble INP G2Elab, Grenoble, France, Grenoble, France; <sup>3</sup>Department of Engineering, The University of Cambridge, Cambridge, United Kingdom; <sup>4</sup>Université de Toulouse; LAPLACE; CNRS; INPT; UPS, Toulouse, France; <sup>5</sup>Dpto. Ciencia de los Materiales, Universidad de Cadiz, Cadiz, Spain.

Diamond is a fascinating semiconductor with exceptional physical properties such as a wide band gap, a high breakdown electric field (10 MV/cm), an outstanding thermal conductivity (20 W/cm/K) and high carrier mobilities. These exceptional properties, or more precisely, the combination of some of these properties makes diamond an ideal semiconductor for high power and/or high frequency electronics which should surpass other materials like silicon, silicon carbide or gallium nitride. Numerous diamond field effect transistors are under investigation: H-terminated accumulation FET, O-terminated inversion channel FET, metal-semiconductor FET and junction FET.

In this work, we propose a new transistor concept in order to exploit the full potentialities of diamond material<sup>1</sup>. The deep depletion concept will be described and proposed for MOSFET devices. A proof of concept of deep depletion diamond MOSFETs will be presented<sup>1,3</sup>. Finally, the recent progresses achieved in terms of device performances will be discussed.

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**9:00 AM \*EP09.08.02/EP08.06.02**

**High Frequency, High Voltage and Vertical Diamond MOSFETs Using Two-Dimensional Hole Gas** Hiroshi Kawarada<sup>1</sup>, Nobutaka Oi<sup>1</sup>, Shoichiro Imanishi<sup>1</sup>, Masayuki Iwataki<sup>1</sup> and Atsushi Hiraiwa<sup>2</sup>; <sup>1</sup>Waseda University, Tokyo, Japan.

**Low SBH for 2DHG:**

Diamond has superior properties as p-type conducting compared with other wide bandgap semiconductors. Among them P-type Schottky barrier height (SBH) is very low ( $< 0.1\text{eV}$ ) on the hydrogen terminated (C-H) diamond surface in high work-function metal such as Au [1]. This property enables hole injection smoothly from metal to diamond subsurface when surface electron potential is high (surface band bends upward). It is realized by negatively charged surface or negative surface voltage bias. Then, 2 dimensional hole gas (2DHG) is produced by hole injection from metal. It is desirable for high speed FET operation [1].

**High Frequency FET:**

The first GHz operation in diamond [2] has been realized by metal semiconductor (MES) FET, where Au is used for source and drain contacts and Al for Schottky gate on the same C-H diamond surface. Al shows the SBH of 0.6 eV, because Al work function is lower than Au by 0.7 eV. The work function dependence of SBH indicates that C-H diamond surface has low surface states density, necessary for MOSFET. In addition to MESFET [3], MOSFETs [4,5] exhibited GHz operation up to 70 GHz [6] in  $f_T$  (cutoff frequency) and  $>100\text{GHz}$  [3] in  $f_{max}$ . The power density is now  $3.8\text{Wmm}^{-1}$  [7] at 1GHz obtained by high bias voltage ( $\sim 50\text{V}$ ). Its electric field is above  $2 \times 10^5\text{Vcm}^{-1}$ , where the hole velocity is nearly saturated in an entire FET. The power density is lower than AlGaN/GaN HEMT, but higher voltage operation can enhance it much further.

**High Voltage FET:**

C-H diamond MOSFETs are uniquely designed for high-voltage ( $\sim 1000\text{V}$ ) and high-temperature (up to  $400^\circ\text{C}$ ) operation using the high temperature ( $450^\circ\text{C}$ ) ALD  $\text{Al}_2\text{O}_3$  as gate oxide and passivation of gate-drain (drift) region. The maximum breakdown voltages ( $V_B$ ) are above  $1500\text{V}$  [8] obtained at long drift region ( $L_{GD} > 15\text{um}$ ).  $V_B/L_{GD}$  is  $\sim 1.0\text{MV/cm}$ , which is equivalent to those of SiC MOSFET and AlGaN/GaN HEMT. The drain current density is comparable to SiC, but 3-4 times lower than AlGaN/GaN at similar  $V_B$ . Conductivity in drift region must be improved by mobility enhancement.

**Vertical FET:**

The first vertical diamond MOSFETs have been developed using 2DHG layer on trench structure [9]. Hole conduction at the trench side wall (3-4 um depth) acts as drift region and is electrically connected to p+ substrate (drain). The drain current density of active planar area has reached to  $5000\text{Acm}^{-2}$  [10], which is comparable to those of SiC or GaN MOSFET. Specific on resistance is  $5\text{m}\Omega\text{cm}^2$  at present.

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**9:30 AM EP09.08.03/EP08.06.03**

**Integration of V2O5 into H-Diamond MOSFETs for Enhanced Device Performance** David Macdonald<sup>1</sup>, Kevin Crawford<sup>1</sup>, Alexandre Tallaire<sup>2</sup>, Riadh Issaoui<sup>2</sup> and David A. Moran<sup>1</sup>; <sup>1</sup>University of Glasgow, Glasgow, United Kingdom; <sup>2</sup>LSPM-CNRS, Université Paris, Paris, France.

As a semiconductor, diamond possesses many unique properties that make it attractive for the production of high performance devices such as robust, high power RF FETs. Such properties include a large bandgap of 5.5 eV, high thermal conductivity of up to  $20\text{Wcm}^{-1}\text{K}^{-1}$  and high carrier saturation velocity of  $2 \times 10^7\text{cm}^{-1}$  for electrons and  $0.8 \times 10^7\text{cm}^{-1}$  for holes. Development of electronic diamond devices has been largely limited however by the immaturity of existing doping processes used to introduce mobile charge into its naturally insulating crystal structure. 'Transfer doping' of hydrogen-terminated diamond (H-diamond) presents a potential solution to this challenge which has allowed for the production of high performance FETs. Stability issues associated with traditional transfer doping, which relies on the presence of atmospheric species on the diamond surface, has limited the maturity of device technologies that exploit these doping techniques. More recently, various work has demonstrated the potential to improve the stability and efficiency of transfer doping in diamond utilising electron acceptor oxide materials on the diamond surface.

In this work, we apply the electron oxide acceptor material V2O5 into H-diamond FET technology and demonstrate substantial performance improvement in comparison with traditional atmosphere-exposed devices. These performance figures include the highest reported drain current and transconductance for a H-diamond FET to incorporate an electron acceptor oxide such as V2O5. Furthermore, a 400C anneal stage utilised in the process flow for devices (as required to ensure stability of the V2O5 layer) is also found to reduce the ohmic contact resistance and increase the carrier concentration beneath the gate of the devices, further improving device performance.

The potential mechanisms for this performance enhancement and future implementation of these techniques to enhance the performance and robust operation of H-diamond FET technology will be discussed.

**9:45 AM EP09.08.04/EP08.06.04**

**Diamond Surface Conduction FET RF Performance Correlated to Internal Charge Carrier Characteristics** Pankaj Shah, James Weil, Khamsouk Kingkeo, Kevin Crawford, Mahesh R. Neupane, Anthony G. Birdwell, Edward Viveiros and Tony Ivanov; Army Research Laboratory, Adelphi, Maryland, United States.

Higher power, higher frequency RF transistors than those possible using the III-nitride semiconductors are desired for large data (high bandwidth) information transmission, highly advanced radar detection, and more efficient communication. We are developing hydrogenated diamond surface conduction field effect transistors (FETs) for use in these next generation RF systems accessing diamond's wide bandgap (5.47 eV) extremely high thermal conductivity ( $> 20\text{W/cm}$ ) and impressive breakdown field (10 MV/cm). Our latest unpassivated, atmospheric transfer doped FETs have maintained high current density performance (up to  $700\text{mA/mm}$  at 10 V) with occasional testing over an 8 month period indicating very limited degradation in an indoor environment and the ability to maintain DC operation powers of  $\approx 7\text{W/mm}$ .

Optimizing RF surface channel FETs is most effectively done using device physics information obtained directly from the same device that the RF measurements are made on. This best connects the influence of material, fabrication steps and structure on performance. In this regard, we obtained the hole velocity in the FET channel using a delay time measurement and this is we believe the first ever discussion of velocity obtained in this way applied

directly on a diamond RF FET. This will be related to carrier density and effective mobility obtained from RF FETs. RF small signal characteristics (current and power gain cutoff frequencies ( $f_t$ ,  $f_{max}$ )) and large signal characteristics (power, gain and efficiency) from load pull measurements will also be discussed for the same devices.

Transit time values obtained from a delay time measurement indicates these FETs have a hole velocity in the channel  $\approx 5 \times 10^6$  cm/s and drain depletion region delay  $\approx 2.5$  ps. On wafer RF measurements for intrinsic current gain cutoff frequency indicate an opposite trend with gate length of  $f_t = 70$  GHz ( $L_g = 50$  nm), 49 GHz, (100 nm), and 10 GHz, (500 nm) when  $V_{ds} = 10$  V. With improved contact and access region resistances we expect the frequency bandwidth to increase. Load pull measurements indicate RF output power densities increased 30% as the drain and gate bias voltage pulse spacing increased (a duty cycle reduction from 5% to 0.5%) suggesting that RF output power is affected by heating of the transfer dopant in unpassivated FETs. These measurements also demonstrate a peak RF output power density of 0.66 W/mm at 2 GHz.

We have also observed that the Schottky barrier heights for the atmospheric transfer doped devices with good gate control are over 0.38 eV and range up to 0.63 eV, however, the ideality factor is quite high (between 1.5 and 7.3). This may be an indication of the roughness of the surface and challenge contacting a hydrogenated region that the gate finger metal sits on. As the gate length reduced from 3 micron down to 50 nm the FET current density increased six fold, and knee voltage reduced uniformly by 50%.

#### 10:00 AM BREAK

#### 10:30 AM \*EP09.08.05/EP08.06.05

**Diamond Power Electronic Devices—Schottky Diodes** Timothy A. Grotjohn<sup>1,2</sup>, John Albrecht<sup>1</sup>, Michael Becker<sup>2</sup>, Ayan Bhattacharya<sup>1</sup>, Ramon Diaz<sup>1</sup>, Aaron Hardy<sup>2</sup>, Timothy Hogan<sup>1</sup>, Matthias Muehle<sup>2</sup>, Robert Rechenberg<sup>2</sup>, Thomas Schuelke<sup>1,2</sup> and Steven Zajac<sup>1</sup>; <sup>1</sup>Michigan State University, East Lansing, Michigan, United States; <sup>2</sup>Fraunhofer USA Center for Coatings and Diamond Technologies, East Lansing, Michigan, United States.

This paper will overview the status and prospects of diamond for power electronics applications. Both the potential and the current/future challenges will be discussed. The particular example of diamond Schottky diodes for power electronics will be explored in more detail. The authors have worked on diamond diodes by developing high quality substrates, low-defect doped epitaxial layers and diamond microfabrication processes. Two diode structures studied are the vertical Schottky diode and the pseudo-vertical diode. The vertical diode requires a thick ( $>250$   $\mu\text{m}$ )  $p^+$  doped substrate and the pseudo-vertical diode requires an undoped substrate with low dislocation defect density. Part of this effort is directed at providing substrates of  $p^+$  diamond to thicknesses  $>250$   $\mu\text{m}$  and providing  $p^+$  epi-layers for the pseudo-vertical devices. Improvement of the  $p^+$  epi-layer deposition was studied by reducing the particles landing on the surface during deposition and increasing the time the diamond CVD reactor can run before soot formed that required the run be terminated. The soot formation is a known problem for diamond deposition using microwave plasma-assisted CVD due to the high boron level added to the deposition process. The boron doped  $p^+$  layer is the region that provides the breakdown voltage of the Schottky diode. The  $p^+$  region needs to be deposited/grown with low dislocation defect density, controlled doping, controlled thickness and low compensation from impurities like nitrogen. The  $p^+$  layer was grown at 800C with a feedgas of hydrogen, methane (4%), oxygen and a small amount of diborane as needed for the desired p-type doping concentration. The addition of the oxygen helps to improve the quality of the epi-layer and reduce passivation of the boron doping by hydrogen. Schottky diodes fabricated showed breakdown voltages exceeding 1800 V. The 1800 V diodes showed forward current densities of up to 300 A/cm<sup>2</sup>. Other diamond diode work will also be overviewed.

#### 11:00 AM \*EP09.08.06/EP08.06.06

**Recent Progress in Diamond Field-Effect Transistor Technologies** Makoto Kasu; Saga University, Saga, Japan.

A diamond semiconductor with a bandgap of 5.47 eV is expected to be the ultimate power device because of its exceptional physical properties, such as a high breakdown field ( $>10$  MV/cm), high mobility, and highest thermal conductivity [20 W/(cm K)]. We previously reported high radio-frequency (RF) power performance of diamond field-effect transistors with a power-gain cutoff frequency,  $f_{MAX}$ , of 120 GHz and an RF output power of 2.1 W/mm at 1 GHz. In this talk, we focus on very recent progress in two basic technologies related to diamond electronics: wafer technology and carrier doping technology.

To overcome the size limitation of diamond crystals, diamond heteroepitaxy technology has progressed rapidly. A 1-inch heteroepitaxial diamond has been demonstrated. In heteroepitaxy, epitaxial overgrowth technology is used to drastically decrease the dislocation density. Furthermore, microneedle technology has been proposed and demonstrated as a method to delaminate heteroepitaxial diamond from its substrate without cracking. [1] In the final process of heteroepitaxy technology, chemical mechanical planarization of the heteroepitaxial diamond surface is important for obtaining a damage-free and smooth surface. The full-width at half-maximum of the (004) plane was as low as 0.03°, and the curvature was 0.29 m, indicating the world's highest quality heteroepitaxial diamond. The size and quality of diamond crystals is improving. We have fabricated diamond field-effect transistors on heteroepitaxial diamond, and the resultant device shows the same drain-current level as conventional homoepitaxial diamond on a HPHT substrate.

Concerning carrier doping technology in diamond, Kubovic and Kasu previously reported NO<sub>2</sub> p-type doping, which they used to fabricate FETs; that is, NO<sub>2</sub>, O<sub>3</sub>, NO, and SO<sub>2</sub> molecules adsorbed onto H-diamond generated hole carriers and the hole sheet concentration was as high as  $\sim 1 \times 10^{14}$  cm<sup>-2</sup> at room temperature. [2] Shiraiishi and Kasu explained this phenomenon as the LUMO/SOMO orbital energies in the inorganic molecules adsorbed onto H-diamond being below the valence-band top of H-diamond, resulting in electron transfer from H-diamond to these molecules. Recently, Geis and Wade at the Massachusetts Institute of Technology investigated the NO<sub>2</sub>-H-diamond surface further by surface chemical techniques such as Fourier transform infrared spectroscopy and elucidated the surface reaction and states. Their reports surprisingly agree with our previous findings. Recently, we used synchrotron X-ray photoelectron spectroscopy/X-ray absorption near-edge spectroscopy and capacitance and conductance measurements to determine the energy band diagram and found oxygen-related states and boundary states in the metal-oxide-semiconductor interface.

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#### 11:30 AM EP09.08.07/EP08.06.07

**Diamond:H/Transition Metal Oxides Transfer-Doping Efficiency and Transistors Performance** Moshe Tordjman<sup>2,1</sup>, Zongyou Yin<sup>3,2</sup>, youngtaek Lee<sup>2</sup>, Alon Vardi<sup>2</sup>, Rafi Kalish<sup>1</sup> and Jesus A. del Alamo<sup>2</sup>; <sup>1</sup>TechNion-Israel Institute of Technology, Haifa, Israel; <sup>2</sup>Microsystems Technology Laboratories, Massachusetts Institute of Technology, Boston, Massachusetts, United States; <sup>3</sup>Research School of Chemistry, The Australian National University, Canberra, Australian Capital Territory, Australia.

Transfer doping of hydrogen terminated diamond (Diamond:H) with various molecular-like surface acceptors suffers from low efficiency and temperature

instability. In contrast, high electron affinity transition-metal oxides (TMOs) (i.e. MoO<sub>3</sub>, WO<sub>3</sub>, V<sub>2</sub>O<sub>5</sub> and ReO<sub>3</sub>), when employed as surface acceptors for transfer doping on Diamond:H, have recently yielded improved p-type sheet conductivity and remarkable thermal stability even with only a few monolayers of coverage<sup>1-4</sup>.

Despite these properties, the realization of Diamond:H electronic devices using TMOs remains very challenging<sup>5,6</sup>. This is due to undesirable changes in the physical and electronic characteristics of the TMO caused by the device fabrication process. In particular, stoichiometry reduction, crystalline phase transitions and structural morphology aggregations take place.

In this work, we will discuss how different TMOs' physical parameters affect the electrical properties of the resulting diamond:H/TMO-based transistors, and how these undesirable effects can be minimized. Electrical and surface characterization monitored before and after transistor fabrication reveal TMO oxygen reduction and a change in its oxidation state leading to electrical conductivity degradation. Based on these findings, we propose and demonstrate a way to improve diamond:H/TMO transistor performance and stability.

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#### 11:45 AM EP09.08.08/EP08.06.08

**3.8 W/mm Power Density at 1GHz for ALD-Al<sub>2</sub>O<sub>3</sub> 2DHG Diamond High Frequency MOSFETs** Shoichiro Imanishi<sup>1</sup>, Nobutaka Oi<sup>1</sup>, Satoshi Okubo<sup>1</sup>, Kiyotaka Horikawa<sup>1</sup>, Taisuke Kageura<sup>1</sup>, Atsushi Hiraiwa<sup>1</sup> and Hiroshi Kawarada<sup>1,2</sup>; <sup>1</sup>Waseda University, Tokyo, Japan; <sup>2</sup>The Kagami Memorial Laboratory for Materials Science and Technology, Waseda University, Tokyo, Japan.

H-terminated diamond with 2 dimensional hole gas (2DHG) provides a promising surface channel for high-power and high-frequency applications due to its excellent properties for FETs. From 2001, mile stones of RF performance of diamond FETs are first GHz operation in MESFETs [1], MISFETs with cutoff frequency ( $f_T$ ) > 20 GHz [2], high power density > 2.0 W/mm [3], maximum oscillating frequency ( $f_{max}$ ) > 100 GHz [4] and  $f_T$  > 50GHz [5]. Particularly, the power density of diamond FETs (up to 2.2 W/mm) [3, 6] is higher than those of GaAs and LDMOS. However, the operating voltage was as low as 15 ~ 20 V because of low breakdown voltage. Power density would be much more improved by realizing high voltage operation. Recently, we reported high average electric field [7] in MOSFETs with Al<sub>2</sub>O<sub>3</sub> deposited as gate insulator [6, 8] and passivation layer [9] by high temperature atomic layer deposition (ALD) [10]. In this work, we fabricated ALD-Al<sub>2</sub>O<sub>3</sub> 2DHG diamond MOSFETs, whose structure is capable of withstanding high voltage, and evaluated small signal and large signal performance at high voltage operation ( $|V_{DS}| \leq 60$  V). As a result, the highest power density of 3.8 W/mm was obtained in diamond.

We fabricated ALD-Al<sub>2</sub>O<sub>3</sub> 2DHG diamond MOSFETs with 100 nm Al<sub>2</sub>O<sub>3</sub> film on IIA-type polycrystalline diamond substrate with a <110> preferential growth surface. The source-gate length, gate length ( $L_G$ ) and gate width were fixed to 0.5, 0.5 and 100  $\mu$ m, respectively and gate-drain length ( $L_{GD}$ ) was ranged from 1 to 3  $\mu$ m.

The drain current density ( $I_{DS}$ ) was -730 mA/mm at  $V_{GS} = -20$  V and  $V_{DS} = -40$  V and the transconductance was 15 mS/mm at  $V_{GS} = 12$  V and  $V_{DS} = -40$  V for  $L_{GD} = 1$   $\mu$ m. Extrinsic  $f_T$  and  $f_{max}$ , including parasitic pad capacitances and inductances, were 30 GHz and 27 GHz at  $V_{GS} = 16$  V and  $V_{DS} = -60$  V for  $L_{GD} = 3$   $\mu$ m.  $f_T = 30$  GHz @  $L_G = 0.5$   $\mu$ m corresponds the saturation velocity of  $1 \times 10^7$  cm/s. It is the first report that diamond FET reaches its saturation velocity. The large signal performance was evaluated using load pull system. The bias point for A-class operation were  $V_{GS} = 12$  V,  $V_{DS} = -50$  V and  $I_{DS} = -405$  mA/mm, respectively. The power density reached 3.8 W/mm at 1 GHz with associated gain of 11.6 dB and power added efficiently of 23.1 % for  $L_{GD} = 2$   $\mu$ m. The power density is the highest ever reported for diamond FETs.

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- [2] H. Matsudaira, H. Kawarada *et al.*: *IEEE Electron Device Lett.* **25** (2004) 480.
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SESSION EP09.09/EP08.07: Joint Session II: Diamond Growth

Session Chairs: Philippe Bergonzo and Travis Wade

Wednesday Afternoon, November 28, 2018

Hynes, Level 2, Room 207

#### 1:30 PM \*EP09.09.01/EP08.07.01

**Heteroepitaxial Diamond—Scaling of an Ultra-Wide-Bandgap Material to Wafer Dimensions** Matthias Schreck<sup>1</sup>, Stefan Gsell<sup>2</sup>, Martin Fischer<sup>2</sup>, Michael Mayr<sup>1</sup> and Björn-Christoph Gallheber<sup>1</sup>; <sup>1</sup>University of Augsburg, Augsburg, Germany; <sup>2</sup>Augsburg Diamond Technology GmbH, Augsburg, Germany.

In the field of power devices, diamond's intrinsic physical properties suggest that they can facilitate ultimate device performance. Just as for other wide-bandgap materials, the availability of wafer-size diamond substrates with high single crystal quality is an indispensable prerequisite. There are two approaches which start from opposite points: First, homoepitaxial growth on carefully selected rather small single crystals with minimum dislocation densities can be performed in such a way that the available area is increased step by step while the dislocation density is kept low. By a similar approach, 4H-SiC has progressively been scaled over 20 years starting from small Acheson platelets to 6" wafer size [1]. The second alternative is based on heteroepitaxy which starts on large areas but with high dislocation densities (DDs). The challenge here consists in a controlled decrease of the DD by several orders of magnitude while preserving the initial size.

This presentation is focused on heteroepitaxy of diamond on Ir/YSZ/Si(001) which has recently provided the first single-crystal diamond wafer with a

diameter > 3.5" and a total weight of 155 carat [2]. All relevant steps for the wafer preparation will be described. First applications of the material will be presented and the potential for further applications will be discussed.

[1] T. Straubinger, R. Eckstein, M. Vogel, A. Weber, presented at 7th International workshop on Crystal Growth Technology, Potsdam, July 02-06 2017.

[2] M. Schreck, S. Gsell, R. Brescia, M. Fischer, *Sci. Rep.* 7, 44462 (2017).

#### 2:00 PM \*EP09.09.02/EP08.07.02

**Engineering Doped Single Crystal Diamond Films for Electronic and Quantum Applications** Jocelyn Achard<sup>1</sup>, Riadh Issaoui<sup>1</sup>, Alexandre Tallaire<sup>1,2</sup>, Ovidiu Brinza<sup>1</sup>, Vianney Mille<sup>1</sup>, Audrey Valentin<sup>1</sup>, André Tardieu<sup>1</sup> and Fabien Bénédic<sup>1</sup>; <sup>1</sup>LSPM-CNRS, Villetaneuse, France; <sup>2</sup>IRCP - Ecole Nationale Supérieure de Chimie de Paris, Paris, France.

Diamond is a transparent wide band gap material with outstanding optical and electronic properties that are attracting a lot of attention for the development of the next generation of devices. Indeed single crystal diamond provides an ideal host material to incorporate different types of impurities that can drastically modify its properties. The use of dopants such as boron can for example allow tuning the electrical conductivity of the film up to the metallic conduction which could allow to produce highly boron doped substrates and develop vertical components whose design and architecture for the realization of more complex function is simpler. In addition nitrogen or silicon are some of the elements that can be introduced in the crystal in order to create optically active centres such as the well-known NV (nitrogen-vacancy) and SiV (silicon-vacancy). Both defects exist in different charge states that can be stabilized depending on the doping level of the diamond.

In this presentation, we will focus more specifically on the production aspects of doped monocrystalline diamond films by chemical vapour deposition assisted by microwave plasma with either boron or nitrogen, highlighting all the constraints inherent to the targeted field of application. In the case of boron doping, particular attention will be paid to showing the plasma conditions which it is essential to maintain in order to obtain a sufficiently thick and doped film leading to on state resistances compatible with their use in vertical components. It will be shown in particular the importance of the gas composition to inject high microwave power allowing coupling high material quality with high growth rate. With regard to nitrogen doping, the conditions for optimizing the formation and orientation of NV colour centres will be discussed and the role of temperature, substrate orientation and gas composition will be highlighted.

#### 2:30 PM BREAK

#### 3:30 PM \*EP09.09.03/EP08.07.03

**Heteroepitaxial Growth of Diamond on 3C-SiC/Si Substrates for Diamond Electronics** Mutsuko Hatano and Takayuki Iwasaki; Tokyo Institute of Technology, Tokyo, Japan.

To realize next-generation power devices and highly sensitive quantum sensors, heteroepitaxy of diamond on Si substrates is a key technology from the viewpoint of scalability and Si CMOS hybrid system [1-3]. We utilize 3C-SiC as an intermediate layer between Si substrates and diamond films because it can be directly grown on the Si and the lattice constant and the surface energy of the SiC are close to the diamond.

We would like to introduce the heteroepitaxial growth of diamond on both Si (001) and (111) substrates by original antenna-edge type microwave plasma CVD with in-situ bias current monitoring during bias enhanced nucleation (BEN). We show the properties of the diamond films, and then the potentials for both power devices (Schottky barrier diodes) and quantum sensors.

Concerning the schottky barrier diodes (SBDs) on heteroepitaxial diamond (001) films, the specific on-resistance of 0.2  $\Omega\text{-cm}^2$  and high rectification of  $10^8$  ( $\pm 5$  V) were obtained which are comparable for SBDs on homoepitaxial diamond films.

The sensor devices using nitrogen-vacancy (NV) centers were formed in the heteroepitaxial diamond (111) films. The NV centers could be preferentially aligned of the NV axis to the one direction and be leading to improving the sensitivity was confirmed.

This work was supported in part by JST-CREST Grant No. JPMJCR1333, KAKENHI (17H01262 and 18H01472), and JSPS Bilateral Open Partnership Joint Research Projects.

[1] M. Schreck, et al., *Sci. Rep.* 7, 44462 (2017).

[2] H. Kawarada, et al., *JAP* 81, 3490 (1997).

[2] J. C. Arnault, et al., *APL* 90, 044101 (2007).

[3] J. Yaita, et al., *APEX* 10, 045502 (2017).

[4] T. Suto, et al., *APL* 110, 062102 (2017).

[5] J. Yaita, et al., *APEX* 11, 045501 (2018).

#### 4:00 PM \*EP09.09.04/EP08.07.04

**Thin CVD Diamond Films on AlGaIn/GaN HEMT Structures** Ken Haenen<sup>1,2</sup>; <sup>1</sup>Institute for Materials Research (IMO), Hasselt University, Diepenbeek, Belgium; <sup>2</sup>IMOMECE, IMEC vzw, Diepenbeek, Belgium.

Diamond's extreme properties make it a prime candidate for next-gen electronic devices, including high frequency and high power operation. While monolithic diamond devices based on doped monocrystalline layers, enabling both unipolar as well as bipolar design schemes, have great potential, the currently obtainable substrate size and quality leave several years of scientific and technological development. The fact that diamond has an extremely high thermal conductivity and can be deposited on non-diamond substrates, opens up an intermediate pathway for hybrid power devices that integrate diamond with other wide bandgap materials such as SiC or GaN. The main goal in such cases is to achieve an enhanced reliability of the latter active materials by providing superior cooling minimizing thermal hotspots and withstanding large break down electric fields.

Here, the case of diamond on GaN-based HEMT structures is considered. First, the deposition of thin CVD diamond layers will be discussed, including the surface chemistry governing the nanodiamond particle seeding, the deposition conditions, and the use of different microwave-based CVD techniques, including resonant cavity and linear antenna technology. Cross-sectional TEM and EELS mapping of the stacks are employed to discuss the structural and morphological properties and to extract possible changes in composition in the underlying  $\text{Si}_3\text{N}_4/\text{AlGaIn}/\text{GaN}$  interfacial layers induced by the substrate temperature during diamond deposition. Finally, the evaluation of the effective thermal conductivity of the thin diamond layers is discussed. The contactless transient thermoreflectance technique, used to study the heat spreading capabilities, shed light on the thermal conductivity and interfacial thermal boundary resistance.

#### 4:30 PM EP09.09.05/EP08.07.05

**Gate Oxide Stability in Diamond Power Transistors** Loto Oluwasayo<sup>1</sup>, Matthieu Florentin<sup>1</sup>, Cedric Masante<sup>1</sup>, Nazareno Donato<sup>3</sup>, Marie-Laure Hicks<sup>4</sup>, Alex C. Pakpour-Tabrizi<sup>4</sup>, Richard B. Jackman<sup>4</sup>, Verena Zuerbig<sup>5</sup>, Philippe Godignon<sup>6</sup>, David Eon<sup>1</sup>, Julien Pernot<sup>1</sup>, Florin Udrea<sup>3</sup>, Daniel Araujo<sup>7</sup> and Etienne Gheeraert<sup>1,2</sup>; <sup>1</sup>University of Grenoble-Alpes, Grenoble, France; <sup>2</sup>University of Tsukuba, Tsukuba, Japan; <sup>3</sup>University of Cambridge, Cambridge, United Kingdom; <sup>4</sup>University College London, London, United Kingdom; <sup>5</sup>Fraunhofer Institute for Applied Solid State Physics, Freiburg,

Germany; <sup>6</sup>Centro Nacional de Microelectronica, Barcelona, Spain; <sup>7</sup>University of Cadix, Cadix, Spain.

Semiconducting diamond is an attractive candidate for the next generation of high voltage and high frequency power devices, thanks to his exceptional properties in terms of wide bandgap, high breakdown field and thermal conductivity. In the literature, several diamond-based field-effect-transistors (FETs) have already revealed good on state performance and high blocking voltage capability (~2kV) in a wide range of operating temperatures. The possibility of generating an inversion regime in diamond metal-oxide-semiconductor FET (MOSFET), and the new Deep Depletion regime (D2MOSFET) specific to wide bandgap semiconductors pave the way for a new generation of power devices. The critical part of the transistor is the gate oxide, with electrical charge traps located within the oxide or at its interface with the semiconductor. These traps can screen the gate potential and shift the threshold voltage, making the devices unusable. The reduction of the trap density is a major concern in all MOS technologies, as well as its stability with time under bias stress.

The latest results about diamond MOS transistors prepared in the framework of the European GreenDiamond project will be presented, and the evolution of the diamond MOS properties with time will be reported for the first time.

#### 4:45 PM EP09.09.06/EP08.07.06

**Diamond Power Electronics—Drift Layer Doping vs Injection Mode Transport** Robert J. Nemanich<sup>1</sup>, Raghuraj Hathwar<sup>1</sup>, Manpuneet Benipal<sup>2</sup>, Franz A. Koeck<sup>1</sup>, Mohamadali Malakoutian<sup>3</sup>, Srabanti Chowdhury<sup>3</sup> and Stephen M. Goodnick<sup>1</sup>; <sup>1</sup>Arizona State University, Tempe, Arizona, United States; <sup>2</sup>Advent Diamond, Tempe, Arizona, United States; <sup>3</sup>University of California - Davis, Davis, California, United States.

The properties of diamond (high mobilities and ultra-gap) suggest different current transport modes that can support high current operation which is sustained and actually improved at high temperatures. This study presents experimental results of forward current density vs voltage which shows a V<sup>2</sup> dependence indicative of injection mode transport. The Schottky-PIN devices show high values of forward current density (> 500A/cm<sup>2</sup> at 3 V) that is stable and actually improves at elevated temperature. Perhaps the most stunning aspect of these results is that the diode specific on-resistance (R<sub>ons</sub>) decreases as the voltage increases. The results indicate a new mode of operation of high mobility diamond power devices where the high carrier mobilities and low phonon scattering will support current injection and drift with a reducing resistance as the current is increased. We present a comparison between diodes that operate in injection mode and the more conventional doped drift layer. We discuss modifications of the standard power electronics figure of merit for projecting the operation of diamond devices that operate in the injection transport mode.

This research is supported through the NASA HOTTECH program.

SESSION EP09.10: FET Devices II  
Session Chairs: Timothy Grotjohn and Robert Nemanich  
Thursday Morning, November 29, 2018  
Hynes, Level 2, Room 207

#### 8:45 AM EP09.10.01

**A Vertical Study by Electron Beam Induced Current and Cathodoluminescence of Diamond Schottky Diode** David Eon<sup>2,1</sup>, Juliette Letellier<sup>1</sup>, Fernando Lloret Vieira<sup>3</sup>, Daniel Araujo<sup>3</sup>, Fabrice Donatini<sup>1</sup> and Maria Pilar Villar Castro<sup>3</sup>; <sup>1</sup>Institut Neel, Grenoble, France; <sup>2</sup>University Grenoble Alpes, Grenoble, France; <sup>3</sup>Department Ciencias de los Materiales, University of Cadiz, Cadiz, Spain.

Diamond electronics devices are probably the future of power electronics in comparison with other wide band-gap materials. This is due to the exceptional intrinsic properties of the diamond such as a wide band gap (5.45 eV), a high breakdown field (10 MV/cm), a large carrier mobility (2000 cm<sup>2</sup>/V.s) and a good thermal conductivity (22 W/cm.K).

The most promising device is the vertical Schottky diode, which has already been the subject to a lot of studies. Nevertheless, there are still some open questions, such as: why leakage current appears in some diodes? Is the leakage current linked to the material itself? Is the interface between the diamond layer and metallic contacts homogeneous and does it have an impact on the diodes characteristics? What is the effect of carrier injection at the p++ interface? Finally, how is the breakdown through the stack? To answer these questions we imagined to observe vertically the structure, i.e. through the Schottky contact, the diamond, up to the heavily doped layer used as the back contact for the diode. Two ways are developed in order to have a view along this direction. First, by focused ion beam technic, a thin lamella is defined and reported on an external holder. Second, by a fine polishing of the edge of the plates, the stack can be directly observed. Thus, with these techniques, all interfaces can be investigated as well as the quality of the grown material. This first part gives us also information on growth and on how to optimize it.

Then, to correlate material properties to electrical properties of Schottky diode, the lamella is wired and studied by electron beam induced current (EBIC). This gives an image of the electric field distribution through all the stack, i.e metal, lightly doped and heavily doped diamond.

It also provides access to the local electric properties of the device and the correlation with the material properties at the same location. The results of this first in-situ electrical measurement of diamond devices will be presented, and all the implications in the understanding of diamond Schottky diodes.

#### 9:00 AM EP09.10.03

**Determination of the Barrier Height of Iridium with Hydrogen-Terminated Single Crystal** Yanfeng Wang, Xiaohui Chang, Wei Wang, Dan Zhao, Jiao Fu and Hong-Xing Wang; Xi'an Jiaotong University, Xi'an, China.

Diamond exhibits many outstanding properties such as good light transmittance, effective resistance to radiation damage, large bandgap, high breakdown voltage, high thermal conductivity, high carrier mobilities etc., having potential applications in the fields of wide range optical transparent window material, coating tools, especially in the field of electron devices which can work in high frequency, high power, high temperature as well as corrosive environment [1-2]. Hydrogen-terminated diamond (H-diamond) devices has been widely researched due to its surface high carrier density and mobility of 10<sup>13</sup> cm<sup>-2</sup> and 50-150 cm<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>, respectively. An excellent ohmic contact between electrode metal layer and H-diamond is needed. Recently, a new ohmic contact between iridium (Ir) and H-diamond has been reported. However, the barrier height between Ir and H-diamond was still not very clear. To obtain the barrier height value between metal and H-diamond, X-ray photoelectron spectroscopy (XPS) technique was used in this work, because it can directly measure the electronic levels, and used to obtain the barrier height value.

For this work, investigation of barrier height between Ir and H-diamond has been carried out using XPS technique. Firstly, 3X3X0.5 mm<sup>3</sup> (001) single crystal diamond with lightly born doping (10<sup>15</sup>/cm<sup>3</sup>) was cleaned by acid and alkali to remove the non-diamond phase. Secondly, the sample was treated by hydrogen plasma to form the hydrogen-terminated diamond surface. Thirdly, 20 nm Ir was deposited on half part of the sample as reference by electron

beam evaporation (EB) technique. Then, anodic aluminium oxide (AAO) with 50 nm hole and 20 nm spacing was transferred on the whole sample surface. After that, 3 nm Ir was deposited on sample by EB technique. Later, after the AAO was removed, 3 nm Ir island with diameter of 50 nm was formed on sample surface. Finally, XPS technique was used to measure the carbon and Ir electronic levels to obtain the barrier height between Ir and H-diamond.

[1] Shozo Kono *et al.*, Electron spectro-microscopic determination of barrier height and spatial distribution of Au and Ag Schottky junctions on boron-doped diamond (001), Japanese Journal of Applied Physics, 53 (2014) 05FP03.

[2] Shozo Kono *et al.*, Direct determination of the barrier height of Ti-based ohmic contact on p-type diamond (001), Diamond & Related Materials 60 (2015) 117-122.

#### 9:15 AM EP09.10.04

**Switching Speed Enhancement with Enlarge Gate width Diamond Cascode Application in High Voltage Half-Bridge Inverter Bi Te<sup>1</sup>**, Takuya Kudo<sup>1</sup>, Aoi Yamamoto<sup>1</sup>, Taichi Yabe<sup>1</sup>, Kiyotaka Horikawa<sup>1</sup>, Toshio Sasaki<sup>2</sup>, Atsushi Hiraiwa<sup>1,2</sup> and Hiroshi Kawarada<sup>1,2,3</sup>; <sup>1</sup>Faculty of Science & Engineering, Waseda University, Tokyo, Japan; <sup>2</sup>Research Organization for Nano & Life Innovation, Waseda University, Tokyo, Japan; <sup>3</sup>Kagami Memorial Research Institute for Materials Science and Technology, Waseda University, Tokyo, Japan.

C-H (Hydrogen-Terminated) diamond MOSFETs shows high breakdown voltage characteristics (over 1600V)<sup>[1]</sup> and wide temperature operations (10K-673K)<sup>[2,3]</sup>. However, transport properties of C-H diamond MOSFETs shows normally-on because 2DHG exists without gate bias voltage. In consideration of these devices and energy-saving the normally-off operation of devices is required.

The cascode structure is based on using the normally-off silicon device to shift the threshold voltage of normally-on device to normally-off. It is successful in changing normally-on AlGaN/GaN HEMT to normally-off. We fabricated the diamond cascode by the combination of the normally-off silicon p-MOSFET and normally-on C-H diamond FET. Characteristics shows the gate of diamond FET is controlled by the silicon p-FET, and it shows normally-off characteristics and maximum transconductance has been drastically enhanced, and the diamond cascode show great breakdown voltage (over 1700V) because the high voltage was blocked by diamond FET.

We applied the diamond cascode in half-bridge inverter configuration as high side, and the GaN cascode (TPH3206PS) is application in low side in the half-bridge inverter. The diamond FET in diamond cascode with  $L_{SG}=2\mu m$ ,  $L_G=4\mu m$ , and gate width is  $25\mu m$ , the  $V_{DS}-I_{DS}$  characteristics shows the maximum current is  $-3.3mA$  with  $L_{GD}=20\mu m$ . After application in half-bridge inverter in the low operation voltage of 20V, the switching time ( $T_{ON}$ ) in the high-side is 40 $\mu s$ . In the high operation voltage of 200V, the  $T_{ON}$  is 60 $\mu s$ , but the switching time ( $T_{OFF}$ ) in the low-side are under 1 $\mu s$ . We think the reason is the gate width ( $W_G$ ) imbalance between the tiny size diamond FET and GaN cascode product, and the gate width imbalance is lead to difference current driving capability between the two sides in inverter. We enlarge the gate width of diamond FETs, and we fabricated the different gate width of diamond FETs from 50 $\mu m$  to 500 $\mu m$ . and  $V_{DS}-I_{DS}$  characteristics shows the maximum current of  $W_G=500\mu m$  is 30mA. After we application the larger  $W_G$  diamond FET in the half-bridge inverter, the  $T_{ON}$  is 5 $\mu s$  in high-side has been observed in the operation voltage of 20V, and  $T_{ON}$  is 14 $\mu s$  in 200V operation voltage, switching time is faster about 8 times in the low voltage and 4 times in the high voltage. At last, we confirmed the half-bridge inverter operated in 400V operation voltage. Therefore, new structure of diamond FETs for higher frequency and high operation voltage half-bridge inverter has been discussed and designed.

[1] H. Kawarada *et al.*, *IEEE IEDM 14933800*, pp.279 -282 (2014) and *ISPSDpp483-486* (2016).

[2] A. Hiraiwa, H. Kawarada, *et al.*, *J. Appl. Phys.* **112**(2012) 124504.

[3] H. Kawarada *et al.*, *Appl. Phys. Lett.* **105**(2014) 013510.

#### 9:30 AM EP09.10.05

**Polycrystalline Diamond Waveguides Realized by Femtosecond Laser Lithography** Haissam Hanafi<sup>1</sup>, Sebastian Kroesen<sup>1</sup>, Georgia Lewes-Malandrakis<sup>3</sup>, Christoph E. Nebel<sup>3</sup>, Wolfram Pernice<sup>2</sup> and Cornelia Denz<sup>1</sup>; <sup>1</sup>Institute of Applied Physics, University of Münster, Münster, Germany; <sup>2</sup>Institute of Physics, University of Münster, Münster, Germany; <sup>3</sup>Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany.

To overcome the limitations and drawbacks of conventional systems, light-based technologies are on the rise. Integrated optical systems offer the potential to realize optimized photonic building blocks into complex circuits exhibiting high stability and scalability. Successful applications of integrated optical systems are already found in telecommunication, metrology and sensing. Examples are also extended to quantum photonic platforms, benefiting mainly from the miniaturization's capabilities that integrated approaches provide.

Established methods to realize integrated circuits, inspired from microelectronics, are limited to quasi-planar geometries and require sophisticated multi-step fabrication routines. The most promising approach to solve these drawbacks and open the route to fast prototyped three-dimensional integrated circuits is femtosecond laser lithography. A femtosecond laser beam is tightly focused inside the volume of a transparent material, mounted on a high-precision translation stage. By translating the sample relative to the beam focus, permanent nanometer-sized structures are induced. Although femtosecond laser lithography was originally intended for waveguide fabrication in isotropic glasses it is not restricted to this host material. To date, femtosecond laser lithography is employed to structure, also organic polymers and the wide class of crystalline materials whereat nonlinear crystals belong to the most important.

Here we report on the fabrication of Type III depressed cladding waveguides in extended polycrystalline diamond samples by femtosecond laser lithography. Previous studies were limited to waveguide fabrication by femtosecond laser in single crystal diamond substrates. Due to the optical properties of diamond, such as high refractive index, strong nonlinear and Raman coefficient, and the ability to host coherent color centers at room temperature, it is attracting increased interest in the fields of classical and quantum photonics. The waveguide structures were inscribed using a femtosecond Ti-sapphire laser system (Coherent Legend) with a central wavelength of 800 nm and pulse duration of about 120 fs at a repetition rate of 1 kHz. The laser beam was focused by a high numerical aperture microscope objective (NA=0.8) into a 300  $\mu m$  thick polycrystalline diamond substrate in an absolute depth of 90  $\mu m$ . We demonstrate waveguiding in the near-infrared telecommunication C-band for optimized processing parameters.

The proposed approach combines the advantages of the versatile technique femtosecond laser lithography with the outstanding material properties of diamond enabling extended 3-dim integrated optical system based on diamond. Promising applications are on-chip diamond quantum photonics and the realization of high-quality single photon emitters.

#### 9:45 AM EP09.10.06

**Hydrogen-Terminated Diamond Field-Effect Transistor with YSZ Dielectric Layers** Yanfeng Wang, Xiaohui Chang, Wei Wang, Dan Zhao, Jiao Fu and Hong-Xing Wang; Xi'an Jiaotong University, Xi'an, China.

Diamond exhibits many outstanding properties such as good light transmittance, effective resistance to radiation damage, large bandgap, high breakdown voltage, high thermal conductivity, high carrier mobilities etc., making it having potential applications in the fields of wide range optical transparent window material, coating tools, especially in the field of electron devices which can work in high frequency, high power, high temperature as well as corrosive environment [1-2]. When diamond is treated by hydrogen plasma, a two dimensional hole gas (2DHG) layer will be formed under diamond surface with a sheet hole density of  $10^{13} \text{ cm}^{-2}$ . However, this 2DHG layer is thermally and chemically instable. In order to solve this problem, dielectric layer is often deposited on H-diamond surface in metal-oxide-semiconductor field effect transistor (MOSFET) field. Up to now, various dielectric layers

have been used in H-diamond MOSFET such as SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, HfO<sub>2</sub>, Ta<sub>2</sub>O<sub>5</sub>, and ZrO<sub>2</sub> *etc.*. Yttria-stabilized zirconia (YSZ) is an excellent dielectric material with high thermal stability, whose dielectric constant and band gap are 27 and 5 eV, respectively.

In this work, the investigation of H-diamond FETs with YSZ dielectric layer has been carried out. Firstly, gold electrodes were patterned on H-diamond by electron beam evaporation technique. Secondly, UV-ozone was used to insulate the device. Then, YSZ dielectric layer was deposited on p-type conduction channels by magnetron sputtering deposition technique. After that, Al gate was deposited on H-diamond by electron beam evaporation technique. The length and width of channel were 15 and 100 nm, respectively. Finally, electrical properties of this H-diamond MOSFET had been investigated. The detail will be presented in the conference.

[1] H. Kawarada, *et al.*, C-H surface diamond field effect transistors for high temperature and high voltage operation, Applied Physics Letters, 105 (2014) 013510.

[2] Yuya Kitabayashi, *et al.*, Normally-Off C–H Diamond MOSFETs With Partial C–O Channel Achieving 2-kV Breakdown Voltage, IEEE Electron Device Letters 38 (2017) 3.

#### 10:00 AM BREAK

SESSION EP09.11: Diamond Devices  
Session Chairs: Ken Haenen and Hiroshi Kawarada  
Thursday Morning, November 29, 2018  
Hynes, Level 2, Room 207

#### 10:30 AM \*EP09.11.01

**Significance of N-Type Fermi Controlling in Diamond Electronics Applications** [Hiromitsu Kato](#), Ogura Masahiko, Toshiharu Makino and Satoshi Yamasaki; AIST, Tsukuba, Japan.

Diamond is considered as an attractive semiconductor to open up next-generation electronics based on its unique physical and electrical properties. For instance, the highest breakdown voltage among wide-band-gap semiconductors with high thermal conductivity and high saturation velocity potentially lead to a higher attainable power density. In addition, the excellent spin characteristics of nitrogen-vacancy complexes including long coherence time and optical initialization and read-out properties lead to a potential candidate for single photon source, magnetic sensors, and quantum applications. High quality single crystal diamond growth by plasma-enhanced CVD and precise control of impurity doping underlay the design of virtually all these applications.

n-type Fermi controlling is still challenging target, since diamond generally prefers to be p-type semiconductor even in an intrinsic diamond. Carbon vacancies including impurity-vacancy complexes are all acceptor-type defects that capture electrons. From the viewpoint of n-type semiconductor diamond, the suppression of these vacancies is one of the most important factors of Fermi controlling as well as suppression of boron acceptors. On the other hand, from the viewpoint of defect engineering, n-type donors can supply electrons to vacancy defects, leading the stabilization of their charge states. Nitrogen-vacancy complexes have three charge states, and only NV<sup>-</sup> centers are required for quantum spin applications.

In this presentation, we would like to discuss the engineering significance of n-type Fermi control from the viewpoints of following two targets. (1) Inversion channel control in diamond/Al<sub>2</sub>O<sub>3</sub> configuration, (2) Phosphorus doping for charge-stage control of nitrogen-vacancy complexes.

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#### 11:00 AM EP09.11.02

**Growth and Characterization of Boron Nitride on Semiconducting Diamond and Its Application to Neutron Detection** [Jesse Brown](#), Jason Holmes, Holly Johnson, Franz Koeck, Ricardo Alarcon and Robert J. Nemanich; Arizona State University, Tempe, Arizona, United States.

Boron Nitride is a wide band gap semiconductor with cubic and hexagonal phases that are isoelectronic to diamond and graphite respectively. The cubic phase of boron nitride has similar structural, electronic, and thermal properties with diamond. These similarities enable an integrated device design that can operate under extreme conditions. We present an approach to deposit boron nitride, as a neutron conversion layer, on a PIN diamond alpha radiation detector. Using plasma enhanced chemical vapor deposition, boron nitride is deposited on polycrystalline and single crystal diamond, with and without a gold contact interlayer. By tuning the hydrogen to fluorine ratio during the deposition, we can control the equilibrium between etching and film formation. *In situ* X-ray photoelectron spectroscopy is used to characterize the sp<sup>2</sup>:sp<sup>3</sup> bonding of the surface, as well as to calculate the growth, etching, and regrowth rates. Our current growth rate is ~1nm/min. The optimal thickness for the neutron conversion layer is 1 to 3µm, therefore we are working toward increasing this growth rate of boron nitride.

This research supported by ARPA-E through the SWITCHES program.

#### 11:15 AM EP09.11.03

**Chemical Vapor Deposited Diamond High Power Capacitors** [Jim I. Davidson](#)<sup>1</sup>, David Kerns<sup>1</sup>, John Fraley<sup>2</sup>, Stephen Minden<sup>2</sup> and Brett Sparkman<sup>2</sup>; <sup>1</sup>Management, International FemtoScience Incorporated, Nashville, Tennessee, United States; <sup>2</sup>Wolfspeed, A Cree Company, Fayetteville, Arkansas, United States.

Utilizing the known dielectric properties of undoped polycrystalline CVD diamond films of > 10e12ohm-cm, capacitor structures were created to examine, for example, the capacitance, charge storage density, leakage and breakdown properties of capacitors whose dielectric layer is commercially procured CVD diamond. This paper will describe the test capacitors created, the testing procedures, and the electrical and physical characterization of the diamond capacitors, "D-Caps".

For power electronics and/or energy storage scenarios, a better capacitor structure, particularly as regards the quality and strength of the dielectric utilized in these capacitors needs to be improved. While high coulomb/cm<sup>3</sup> values are cited by, e.g., electrochemical and electrolytic ultracapacitor type capacitors, their high voltage limitations are disappointing, and by virtue of their fundamental makeup cannot be enhanced. There are advantages to having truly solid, planar (layered) type of capacitor structure, such as presently achieved with, for example, ceramic type capacitors. There have been laboratory tests of the dielectric strength/ voltage breakdown characteristics of diamond layers – and those values (circa > 3(10e7) V/cm) are impressive - but no practical

examination for capacitor applications derived directly from commercially deposited polycrystalline diamond films has been performed.

This paper takes commercially procured undoped polycrystalline diamond films and fabricates them into practical conductor/ diamond /conductor layered capacitor structures and examines their electrical behavior and their potential [figuratively and literally] for utilization as industrial capacitors for power or energy storage. MDM (metal/diamond/metal) layers, typically 1 to a few microns in thickness, were examined by SEM, Xray and Raman spectroscopy topologically and in cross-section. Aspects of multilayer “comb” type interlayer (“MDMDM” structures) were considered.

We will report pertinent electrical and physical characterization properties of planar diamond dielectric based capacitor test structures, including leakage characteristics, breakdown behavior, statistical distribution of yield and routes to practical packaging and applications.

Acknowledgement: this Work supported by the ARPA-E/IDEAS program, “Compact, High Voltage, High Energy Density Diamond Capacitors for Power Electronics Applications”, Contract Number: DE-AR0000838.

11:30 AM EP09.11.04

**Nitrogen and Oxygen-Terminated Diamond Electrolyte Solution-Gate FET for pH Sensing in Both Acidic and Alkaline Solutions in pH Solutions** Yu Hao Chang<sup>1</sup>, Shaili Falina<sup>1</sup>, Sora Kawai<sup>1</sup>, Mohd Syamsul<sup>1</sup>, Yutaro Iyama<sup>1</sup>, Yukihiko Shintani<sup>1</sup> and Hiroshi Kawarada<sup>1, 2</sup>; <sup>1</sup>Waseda University, Tokyo, Japan; <sup>2</sup>Kagami Memorial Research Institute for Material Science and Technology, Tokyo, Japan.

We investigated pH sensitivity of nitrogen and oxygen-terminated diamond electrolyte solution-gate field effect transistors (SGFETs). Diamond has many appealing properties including chemical inertness, biocompatibility, and simple chemical modification on the surface that are suitable for pH sensing in SGFETs. Since 2001, we have reported diamond SGFETs where the semiconductor surface was directly immersed in electrolyte solution and the drain current was controlled by electric double layer at the diamond surface [1]. We conducted H-termination on diamond surface to obtain surface p-type conductivity and introduced O-termination to acquire pH sensitivity [2]. Amine-terminated diamond SGFETs has a pH sensitivity of 50 mV/pH; the amine termination was achieved by UV radiation treatment in NH<sub>3</sub> atmosphere [3]. In recent research, N-termination can be achieved on diamond surface by nitrogen radical exposure with remote RF plasma [4]. In this work, we continued to utilize nitrogen and oxygen-termination on diamond SGFETs for pH sensing in both acidic and alkaline solutions as illustrated in Dr. Shaili Falina's research [5], and increased coverage rate of N-terminated surfaces to optimize pH sensitivity.

Polycrystalline diamond surface was first hydrogenated by plasma treatment under hydrogen atmosphere. At room temperature, H-terminated diamond surface exhibited sheet resistance of 20-60 kΩ/sq and a high carrier density at 10<sup>13</sup> cm<sup>-2</sup>. Source and drain electrodes were then formed with Au, connected with wires by conductive paste and sealed with epoxy resin to prevent leakage in pH solutions. The resulting channel length and width was 0.33 mm and 5.0 mm, respectively. As opposed to UV ozone treatment, anodic oxidation was conducted to achieve O-termination [6]; the channel of diamond surface is applied up to 1.6 V while the Ag/AgCl reference electrode was grounded. Finally, N-termination was conducted by means of remote RF plasma at 300 W with nitrogen gas containing 4% hydrogen gas as radical source for 20 minutes. I<sub>DS</sub>-V<sub>DS</sub> characteristics and pH sensitivity were procured by Keithley Instrument source-measure unit from pH 2-12.

As a result, nitrogen and oxygen-termination on diamond SGFETs showed increased pH sensitivity compared with only O-termination in both acidic and alkaline solutions. While further investigation regarding the effect of N-terminated surface coverage rate in pH solution is required, by increasing the coverage rate of N-terminated surface, we suspect an enhancement in pH sensitivity of the device.

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11:45 AM EP09.11.05

**Electrical Properties of CMP Treated 1 inch Heteroepitaxial Diamond Substrates** Seongwoo Kim<sup>1</sup>, Yuki Kawamata<sup>1</sup>, Yutaka Kimura<sup>1</sup>, Kokichi Fujita<sup>1</sup>, Kenjiro Ikejiri<sup>1</sup> and Makoto Kasu<sup>2</sup>; <sup>1</sup>Adamant Namiki Precision Jewel Co., Ltd., Tokyo, Japan; <sup>2</sup>Saga University, SAGA, Japan.

Mass production technologies of diamond substrate are important to accelerate research and development activities of diamond semiconductor. Although there still exists some challenges, such as large substrate, high crystallinity and surface finishing, most of research resources are devoted to achieve high crystallinity. In order to overcome the other two tasks, we have developed heteroepitaxial diamond growth method and Chemical Mechanical Planarization (CMP) technologies.

Heteroepitaxial diamond growth method has a great potential to obtain a large diamond substrate compared to other growth methods. Because of the difference in the coefficient of thermal expansion between diamond and basal substrate material, crack and random delamination are generated in diamond film during the cooling down process. We have previously reported in details the fabrication of the freestanding heteroepitaxial diamond substrate via microneedles that prevent the crack generation and the delamination<sup>1)</sup>. Following this technique, a diamond substrate with 1 inch diameter was successfully achieved. In order to demonstrate larger than 1 inch diameter diamond substrate, it is necessary to change the basal substrate material because of two reasons: (1) the diameter of the commercially available MgO substrate is limited to 1 inch. (2) MgO substrate cost exponentially increases with diameter. One of the most promising materials to replace MgO is sapphire. The crystal system of sapphire (hexagonal) is different from that of diamond and iridium (Cubic), whereas sapphire substrate is chemically inert, 8 inch substrate available and much cheaper than MgO. Therefore, standard hetero-epitaxial diamond growth procedure on MgO substrate was applied to the A-plane sapphire substrate with 10 mm × 10 mm square surface. The grown crystal was obtained without any cracks and breakage. The obtained thickness is 800 μm. As a result of X-Ray Rocking Curve measurement, crystallinities of both (400) and (311) planes were better than that achieved diamond grown on MgO substrate. Furthermore, 1 inch heteroepitaxial diamond substrate was successfully demonstrated on sapphire.

Surface finishing is important to obtain the best performance of a substrate. In the case of conventional semiconductor substrate, CMP is applied as a surface finishing technology. The influence of CMP treatment on heteroepitaxial diamond was investigated by MOSFET characteristics. The heteroepitaxial diamond substrates were all the same thickness, off angle and surface roughness by mechanical polishing. CMP was applied after mechanical polishing. MOSFET was fabricated on the heteroepitaxial diamond substrate with and without CMP. We found that the Id-Vd characteristics of MOSFET on CMP treated substrate is better than that without CMP. The details will be discussed at the symposium.

1) H. Aida et. al., Appl. Phys. Express9, 035504 (2016)

**1:30 PM \*EP09.12.01**

**Funcionalized Nanodiamond for Photocatalytic Applications** [Anke Krueger](#); Institut für Organische Chemie, Wuerzburg University, Wuerzburg, Germany.

The direct use of CO<sub>2</sub> as a feedstock for the production of fuels and chemical building blocks is an important research goal these days. Especially the direct photocatalyzed transformation of the greenhouse gas using solar light is very important as it will enable higher efficiencies by avoiding the intermediate transformation of solar energy to electrical energy. In general, the photocatalytic transformation of carbon-based starting materials is attractive as such reactions environmentally friendly and can be carried out under mild conditions.

Diamond is an attractive material for the photocatalytic transformations due to its unique electronic properties, e.g. the reduction of carbon dioxide.<sup><span style="font-size:10.8333px">1</span></sup> So far, the excitation of electrons into the conduction band requires UV light due to the large bandgap. Therefore, for the ability to use visible light, the introduction of unoccupied states in the band gap of diamond is a requirement to overcome this limitation.

In this work we report our results on the photocatalytic activity of differently terminated and functionalized diamond materials. This includes not only direct termination with suitable surface atoms but also the immobilization of transition metal complexes using different linker strategies. We were able to demonstrate the direct use of visible light for the transformation of CO<sub>2</sub> into methanol and formate and will discuss the influence of different parameters such as the medium, surface structure and type of diamond on the efficiency of the photocatalytic process.

This project has received funding from the European Union's Horizon 2020 Program under Grant Agreement no. 665085 (DIACAT).

**References**

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**2:00 PM EP09.12.02**

**Tunable Nanodiamond Surfaces using Silica-based Chemistry for Functionalization and Bioimaging** [Pomaikaimaikalani Yamaguchi](#)<sup>1</sup>, [Perla J. Sandoval](#)<sup>1</sup>, [Karen Lopez](#)<sup>1</sup>, [Anida A. Len](#)<sup>1</sup>, [Andres Arreola](#)<sup>1</sup>, [Virginia Altoc](#)<sup>2</sup>, [Dennis Nordlund](#)<sup>3</sup> and [Abraham Wolcott](#)<sup>1</sup>; <sup>1</sup>San Jose State University, San Jose, California, United States; <sup>2</sup>The Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, California, United States; <sup>3</sup>SLAC National Accelerator Laboratory, Menlo Park, California, United States.

The interest in high-pressure high-temperature (HPHT) fluorescent nanodiamonds (FNDs) as an emerging probe for biosensing results from the unique photophysics of the nitrogen vacancy center (NVC). NVCs detect magnetic fields, electric fields, and may be realized as pH or voltage sensors. Attractive characteristics for biosensing include their lack of cytotoxicity, infrared emission (575-800 nm) and long term photostability make FNDs an ideal bio-labeling tool. Challenges in modifying the inert diamond surface limit their development as a biological probe in cells and tissues. The synthesis of a silica shell using wet chemistry techniques encapsulating the FNDs allows for further functionalization and control of shape specific properties. Silica priming of the diamond surface proceeds by nucleophilic attack of the tetrahydroxysilane precursors forming a silyl ether bond (C-O-Si-OH<sub>3</sub>) to the diamond surface. A realization of 2-20 nm thick shells of SiO<sub>2</sub> was achieved through variations in synthesis time and particle size analysis was conducted through DLS, SEM, and TEM. Molecular functionalization of polyethylene glycol (PEG) moieties onto the silica shell stabilizes the FNDs colloiddally in biological environments while amine and sulphydryl moieties act as anchors for folic acid decoration. Other functionalization techniques employed include the use of 11-azidooundecyltriethoxysilane, (3-Glycidoxypropyl)trimethoxysilane, (3,3,3-trifluoropropyl)-trimethoxysilane, carboxylic acid, and phosphate moieties. Functionalization was verified through FTIR and synchrotron based X-ray techniques (XAS and XPS). We also demonstrated optimized targeted staining of upregulated folate receptors in HeLa cell cultures. This work provides a wide range of surface and morphological tunability that can be used in magnetometry and electric field sensing applications.

**2:15 PM EP09.12.03**

**Stable Ag-Diamond Core-Shell Nanostructures with Tunable Optical Properties** [Shuo Li](#) and [Robert J. Hamers](#); University of Wisconsin-Madison, Madison, Wisconsin, United States.

Diamond is widely used in many applications like coatings, optical lenses & windows, high power laser optics, photocatalysts and imaging fields. Tuning the optical properties of diamond is needed for wider applications. However, diamond is a large bandgap material and is highly transparent from deep UV to infrared light across the electromagnetic spectrum, limiting its applications. Previously people use doping method by introducing impurities like nitrogen or boron into diamond crystal lattices, creating defect states which absorb visible light and generate colors. However, there are only limited choices of elements available to serve as donors, limiting the tunability of diamond optical properties. Moreover, the introduction of impurities would often result in the degradation of diamond quality. Plasmonic metal nanoparticles are highly efficient at absorbing and scattering light at certain wavelengths, and they exhibit size- and shape-dependent plasmonic features in a wide region of the spectrum. Therefore, by integrating metal nanoparticles like Ag into diamond would provide an alternative approach to tune the diamond's optical properties in a more controllable way. Previous reports have shown the incorporation of Ag nanostructures with diamond would enhance the optical properties of diamond. Whereas for as-reported Ag-diamond hybrids, the Ag are exposed to the environment, which makes the structures not stable; the tunability of Ag plasmonic properties also needs to be increased.

Here we demonstrate a stable Ag-diamond core-shell structure can be made, in which the Ag core sizes and diamond shell thicknesses can be controlled precisely, resulting in the tunable optical properties of diamond. As Ag is embedded in diamond shells, this hybrid material has superior stability that can maintain the structure and properties even after high temperature annealing or acid boiling treatment. The Ag nanoparticles embedded within diamond films are grown by a three-step process: (1) a very thin film of Ag is deposited onto a diamond surface, (2) the Ag film is de-wetted into individual nanoparticles, and (3) a second diamond film is grown to encapsulate the Ag nanoparticles. Cross-sectional SEM clearly shows individual nanoparticles with sizes ranging from ~10 nm to 500 nm depending on experimental conditions. UV-vis spectra clearly show the plasmonic peaks in good correspondence of SEM. TEM analyses show the boundary between the diamond-Ag nanostructures, as well as the columnar growth of diamond extending radially from the Ag nanoparticle cores. We show that the unique Ag-diamond core-shell structure with great stability is a promising platform for diamond with tunable optical properties in various applications.

**2:30 PM EP09.12.04**

**Black Diamond as an Antibacterial Surface—Interplay Between Chemical and Mechanical Bactericidal Activity** [Paul W. May](#)<sup>2</sup>, [Olivia Dunseath](#)<sup>2</sup>, [Ed J. Smith](#)<sup>2</sup>, [Tarik Al-Jeda](#)<sup>2</sup>, [James A. Smith](#)<sup>2</sup>, [Angela Nobbs](#)<sup>1</sup>, [Gavin Hazell](#)<sup>1</sup> and [Colin C. Welch](#)<sup>3</sup>; <sup>1</sup>Dental School, University of Bristol, BRISTOL, United Kingdom; <sup>2</sup>School of Chemistry, University of Bristol, Bristol, United Kingdom; <sup>3</sup>Plasma Technology, Oxford Instruments, Bristol, United Kingdom.

'Black silicon' (bSi) samples with surfaces covered in nanoneedles of length  $\sim 5 \mu\text{m}$  were fabricated using a plasma etching process and then coated with a conformal uniform layer of diamond using hot filament chemical vapour deposition to produce 'black diamond' (bD) nanostructures. The diamond needles were then chemically terminated with H, O,  $\text{NH}_2$  or F using plasma treatment, and the hydrophilicity of the resulting surfaces were assessed using water droplet contact-angle measurements. The effectiveness of these differently terminated bD needles in killing the Gram-negative bacterium *E. coli* was semi-quantified by Live/Dead staining and fluorescence microscopy, and visualised by SEM. The total number of adhered bacteria was consistent for all the nanostructured bD surfaces at around 50% of the value for the flat diamond control. This, combined with a chemical bactericidal effect of 20-30%, shows that the nanostructured bD surfaces supported significantly fewer viable *E. coli* than the flat controls. The bD surfaces were particularly effective at preventing the establishment of bacterial aggregates – a precursor to biofilm formation. The percentage of dead bacteria also decreased slightly as a function of hydrophilicity, with superhydrophobic F-terminated bD killing 50% of the adherent bacteria. These results are consistent with a predominantly mechanical mechanism for bacteria death based on the stretching and disruption of the cell membrane, combined with a smaller additional effect from the chemical nature of the surface.

#### 2:45 PM EP09.12.05

**Production and Manipulation of Diamond Nanoparticles** Laia Gines, Soumen Mandal and [Oliver A. Williams](#); Cardiff University, Cardiff, United Kingdom.

The production of diamond nanoparticles containing colour centres has attracted increasingly interest in the last years for quantum computation applications. Particularly, the SiV colour centre has highlighted as a promising photon source among other colour centres in diamond, due to its interesting optical properties at room temperature. SiV colour centres acting as single photon emitters can be created through different approaches in-situ during CVD growth by introducing silicon as a solid source or in a gas phase.

In this work diamond nanoparticles with custom colour centres were produced from bulk material via milling strategies. First a diamond film containing NV/SiV centres was grown onto a passive substrate, followed by sacrificial etching of the substrate. The resulting diamond film was milled using a planetary mill based on either steel or SiN. The milled material was purified by acid reflux. To measure particle sizes, different slurries containing the diamond nanoparticles obtained were prepared and characterized by using Dynamic Light Scattering (DLS) and Nanoparticle Tracking Analysis (NTA). XPS was also used to qualify the milling process contamination. Colour centre incorporation was confirmed by Photoluminescence and Hanbury Brown and Twiss measurements. The control of surface  $\text{sp}^2$  and zeta potential will also be demonstrated.

#### 3:00 PM BREAK

#### 3:30 PM EP09.12.06

**Increasing Reactivity of HPHT Nanodiamond Surfaces via Direct Amination** [Jocelyn Valenzuela](#)<sup>1</sup>, Cynthia Melendrez<sup>1</sup>, Grace Jean-Pierre<sup>1</sup>, Polo Tran<sup>1</sup>, Alejandro Hernandez<sup>1</sup>, Dennis Nordlund<sup>2</sup> and Abraham Wolcott<sup>1</sup>; <sup>1</sup>San Jose State University, San Jose, California, United States; <sup>2</sup>SLAC National Accelerator Laboratory, Menlo Park, California, United States.

Increasing the reactivity of fluorescent nanodiamonds (FND) containing nitrogen vacancy centers (NVC) surfaces is a challenge due to steric hindrance, high atomic surface density (22 atoms/nm<sup>2</sup> on 110 surface) and poor leaving group properties. Developing a deeper understanding of surface chemistry and providing robust chemical protocols can advance FND uses in sensing applications. FNDs are an attractive fluorophore for biolabeling due to their electron spin properties, all-carbon matrix and long-term photostability, but have not been fully utilized as an active sensor in biological systems. The surface chemistry of HPHT NDs, a current bottleneck in the fields' progress, plays a vital role in colloidal stability, bioconjugation and NVC photophysics. This project focuses on the modification of HPHT ND surfaces with amine chemistry through gas and liquid phase chemistry. Past investigations showed that oxidized HPHT NDs have an alcohol-rich surface similar to bulk diamond. Following the bromination of the oxidized HPHT NDs, direct amination chemistry was carried out in a high temperature three-zone tube furnace with reactive gases from 200-700°C. Aminated NDs were characterized with X-ray absorption, XPS, and FTIR spectroscopies. XAS nitrogen K-edge spectra are suggestive of multiple C-N bond orders including amines, imines and nitriles. Our goal is to form a homogenous amine (-NH<sub>2</sub>) terminated surface that will increase reactivity. Overall, the reactive amine groups provide a strong foundation for further chemistry, such as antibody/antigen conjugation, small molecular library screening and neuron membrane staining.

#### 3:45 PM EP09.12.07

**Applied Particulate Nanodiamond to Enhance Thermal and Mechanical Properties of Host Systems** [Jim I. Davidson](#)<sup>1</sup>, David Kerns<sup>1</sup>, Blake Branson<sup>1</sup>, Ethan Languri<sup>2</sup>, Farzin Mashali<sup>2</sup>, Wayne Johnson<sup>2</sup>, Lino Costa<sup>3</sup> and Kathleen Lansford<sup>3</sup>; <sup>1</sup>FemtoSci Incorporated, Nashville, Tennessee, United States; <sup>2</sup>Tennessee Technological University, Cookeville, Tennessee, United States; <sup>3</sup>University of Tennessee Space Institute, Tullahoma, Tennessee, United States.

Conventional heat transfer fluids such as water, ethylene glycol, mineral oils and their mixtures are presently significantly compromised for their fundamental objective, cooling the heat generating system, because their inherent thermal conductivity is poor. Likewise, the inherent strength of, for example, polymer based solid systems could be enhanced by the addition of nanoparticles that improve bonding at the molecular level. In this paper, particulate nanodiamond, ND, ["detonation" nanodiamond] is examined as a low concentration additive to liquid and solid systems to enhance, e.g., their thermal conductivity and strength.

The criticality of sufficient *deaggregation* and compatible *functionalization* chemistry to successful outcomes will be addressed. We have prepared different functionalized nanodiamond, FND, samples, where the functional group is specifically intended to have its terminal chemical bonding couple with the host matrix resulting in their operating improvement. Because the effective diameter of molecular influence of the attached functional groups in the host matrix can be much greater than the 5 nanometers of the "core" ND, concentrations in the range of ppm of the FND can result in double digit improvements of key properties

Examples of these FND applications will be presented, such as, many cooling loop systems, be they for electronics or engines, are *water* based. We have examined a FND formulation and evaluated it as an additive in a precisely controlled and monitored water cooling loop which allows the direct determination of the *heat transfer coefficient*, a more practical parameter than thermal conductivity, and an improvement of over 20% was observed at a FND concentration of 500ppm.

Further, an appropriate FND formulation to enhance the *polymers* used in composites was applied and improvement in the flexural strength was observed. Tensile strength testing of ox-ND/PAN (highly de-aggregated nanodiamond (ND)/ polyacrylonitrile (PAN)) and ox-UDD/PAN (aggregated ultra-dispersed (UDD)/ polyacrylonitrile (PAN)) thick-film composites was performed. Elastic modulus, tensile strength, and elongation measurements of these solid polymer samples as a function of ND addition were measured. The more highly dispersed de-aggregated ox-ND is more effective as a reinforcement additive than aggregated ox-UDD while the as-received UDD/PAN composite samples, having very poor dispersion characteristics [a configuration often examined and reported in some ND evaluations], exhibit tensile strengths even lower than those measured for pure PAN control films. The results of this work demonstrate the elastic modulus and tensile strength of de-aggregated ox-ND/PAN composites outperform those of aggregated ox-UDD/PAN composites at all additive concentrations above  $\sim 3 \text{ vol.}\%$ . At 10 vol.% ox-ND loading, *elastic modulus is enhanced by nearly 80% and tensile strength*

increases by nearly 60% relative to pure PAN films.

#### 4:00 PM EP09.12.08

**Neuron Adhesion on Diamond—Competition Between Polymer Treatment and Surface Morphology** Barbora Jakubcova<sup>2</sup>, Andrew Taylor<sup>3</sup>, Pavel Hubik<sup>3</sup>, Vaclav Petrak<sup>2</sup> and Vladimira Petrakova<sup>1,2</sup>; <sup>1</sup>Institut for Experimental Physics, Freie Universitaet Berlin, Berlin, Germany; <sup>2</sup>Faculty of Biomedical Engineering, Czech Technical University in Prague, Kladno, Czechia; <sup>3</sup>Institute of Physics, The Czech Academy of Sciences, Prague, Czechia.

The ability to form an efficient interface between material and neural cells is a crucial aspect for construction of neuroelectrodes. Diamond offers material characteristics that could, to a large extent, improve the performance of neuroelectrodes. The greatest advantage of diamond is a large variety of material and surface properties such as electrical conductivity, surface morphology, and surface chemistry. Such a variety of material characteristics can lead to various cellular responses. Here we compare survival, adhesion, and neurite formation of primary neurons on diamond thin films of various morphologies and treatments with several types of polymers commonly used to enhance cell adhesion. We found that the variation of surface roughness of nanocrystalline diamond film when coated with polymer does not have a major influence on neuron survival or adhesion. The adhesion of neurons can be influenced by the selected type of polymer coating. High molecular weight of polyethylenimine resulted in lower viability, adhesion and neurite formation. The addition of laminin to treated films did not lead to significant improvements in neuron adhesion and neurite development. Our findings emphasize the importance of the correct polymer treatment over morphological properties of diamond thin films as a material for forming interfaces with primary neurons.

Reference:

Jakubcova B., and Petrakova V. et al., Neuron adhesion on diamond: Competition between polymer treatment and surface morphology, *Advanced Engineering Materials*, 2018, <https://doi.org/10.1002/adem.201800182>

#### 4:15 PM EP09.12.09

**Mussle-Inspired Encapsulation of Fluorescent Nanodiamond into Polydopamine shells for Biomedical Applications** Haksung Jung, Kyung-Jin Cho, Yeonee Seol, Yasuharu Takagi, Andrew Dittmore, Paul Roche and Keir C. Neuman; National Institutes of Health, Bethesda, Maryland, United States.

Fluorescent nanodiamonds (FNDs) have been considered as promising nanomaterials for biomedical application such as cell labeling, imaging, and sensing. However, persistent challenges remain in integrating FND technology into biomedical applications. These challenges include poor colloidal stability in physiological solutions and difficulty in functionalizing FNDs. Here, inspired by the adhesive protein of marine mussels, we demonstrate a method of encapsulating FNDs in a polydopamine (PDA) shell. We further describe surface modification of the PDA encapsulated FND with thiol terminated PEG (PEG-SH), which enhances colloidal stability and biocompatibility, while also providing a modular approach for conjugating functional molecules to the FND@PDA particles. Thiol terminated methoxy PEG functionalized FND@PDA are utilized as fluorescent probes for imaging of immature bone marrow derived dendritic cells. The PEGylated FND@PDA is taken up by the cells and exhibits reduced nonspecific membrane adhesion. In a second example, biotin-PEG-SH functionalized FND@PDA is conjugated with biotinylated DNA via streptavidin-biotin interaction, permitting long-term single-molecule fluorescence-based tracking. The robust polydopamine encapsulation method that we present provides an avenue for the development of FND as multifunctional labels, drug delivery vehicles, and targeting agents for biomedical applications.

#### 4:30 PM EP09.12.10

**Hydrogenation Effects on Interfacial Thermal Conductance at Grain Boundaries of Ultrananocrystalline Diamond Films** Satoshi Takeichi<sup>1</sup>, Takashi Nishiyama<sup>2</sup>, Mitsuru Tabara<sup>1</sup>, Shuichi Kawawaki<sup>1</sup>, Masamichi Kohno<sup>1</sup>, Koji Takahashi<sup>1</sup> and Tsuyoshi Yoshitake<sup>1</sup>; <sup>1</sup>Kyushu University, Fukuoka, Japan; <sup>2</sup>Fukuoka University, Fukuoka, Japan.

Diamond is one of ideal hard coating and heat sink materials due to the highest thermal conductivity ( $2 \times 10^3$  W/(m K)) among materials, owing to extremely low phonon scattering. Since phonon scattering is drastically enhanced by grain boundaries, the thermal conductivity of polycrystalline diamond films is strongly dependent on the grain size. The grain size dependent of thermal conductivity of diamond has been mainly studied for chemical vapor deposition (CVD), and it has been reported that thermal conductivity is strongly depends on the intrinsic properties of grain boundaries. Recently we have realized the formation of UNCD/hydrogenated amorphous carbon (a-C:H) composite (UNCD/a-C:H) films by coaxial arc plasma deposition (CAPD), which is a kind of physical vapor deposition. Note that CAPD does not necessarily require a hydrogen atmosphere during the deposition for the formation of diamond grains, in other words, UNCD/non-hydrogenated amorphous carbon (a-C) composite (UNCD/a-C) films can be grown under a base pressure. So far, hydrogenation effects on the thermal conductivity of UNCD/a-C(:H) films has never been studied because H atoms are unintentionally incorporated into the films from source gases in CVD. In this study, UNCD/a-C and UNCD/a-C:H films were deposited under a base pressure and in hydrogen atmospheres, and the hydrogenation effects on the interfacial thermal conductance at grain boundaries were studied. UNCD/a-C:H and UNCD/a-C films were deposited on Si substrates at a substrate temperature of 550 °C by coaxial arc plasma deposition (CAPD) using a coaxial arc plasma gun equipped with a graphite target. Al films were deposited on the UNCD/a-C(:H) films by sputtering for the time-domain thermoreflectance (TDTR) measurement.

From the TDTR measurement, the thermal conductivities of the non-hydrogenated and hydrogenated films were estimated to be 7.80 and 2.32 W/(m K), respectively, which are larger than those of a-C:H and a-C films, respectively. It might be because of the existence of diamond crystallites in our films. The interfacial conductances in grain boundaries of the non-hydrogenated and hydrogenated films are estimated to be 4892 and 1010 MW/(m<sup>2</sup> K), respectively. As reasons for the small interfacial conductance value of the hydrogenated film as compared with that of the non-hydrogenated film, we consider that the number suppression of carriers generated from sp<sup>2</sup> bonds, which contribute heat transport, and the existence of hydrogen atoms at grain boundaries in the hydrogenated films that enhance from phonon scattering. It was experimentally demonstrated that the thermal conductivity of UNCD/a-C(:H) films sensitively decreases by hydrogenation, in other words, the thermal conductivity of UNCD/a-C(:H) films is controllable with hydrogenation.

#### 4:45 PM EP09.12.11

**High Self-Nucleation for Continuous Nano-Diamond Film Growth on Silicon Substrate** Shulin Gu, Yang Shen, Kun Tang, Jiandong Ye, Shunning Zhu, Qianqian Du, Licai Hao and Youdou Zheng; Nanjing University, Nanjing, China.

Continuous diamond films grown on heterosubstrates are required for current technological applications, such as heat dissipation, nano/micro-electromechanical systems and even future potential many optic-electronic devices. Growth of thin coalesced diamond layers requires a very high density of nucleation sites (typically  $10^{11}$  cm<sup>-2</sup>). However, very low nucleation densities (typically below  $10^5$  cm<sup>-2</sup>) are obtained on non-treated substrates due to the high surface energy of diamond relative to heterosubstrates. Seeding process or surface pretreatment is believed to be the best choices to provide stable diamond seeds or nuclei for subsequent diamond CVD growth, but surface damage (microscopic defects or scratches) caused during seeding or pretreatment process has hindered its application on future potential optic-electronica devices. A promising alternative is to develop a high self-nucleation method for subsequent diamond growth on non-diamond surfaces.

It is a generally accepted fact, that the primary process responsible for diamond nuclei formation is heterogeneous nucleation on the substrate surface. In

the case of Si substrates, the nucleation occurs on the  $\beta$ -SiC intermediate layer (several nm) at high temperatures, when the carbon concentration on the substrate surface reaches its saturated value. The nucleation densities can then be enhanced by one to two orders, but this value is still far below the minimum requirements for subsequent continuous film growth.

In this presentation, we will report our recent observations on high self-nucleation of continuous thin nano-diamond films growth on silicon substrate. The effect of the substrate orientation and seeding process will be compared. The possible cause for such self-nucleation phenomenon will be investigated and discussed.