SYMPOSIUM G

Materials, Integration, and Packaging Issues for High-Frequency Devices II

November 29 - December 1, 2004

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* Invited paper

SESSION G1: Tunable/High k Thin Films I
Chairs: Yong S. Cho and Paul Muralt
Monday Morning, November 29, 2004
Liberty (Sheraton)

8:30 AM *G1.1
Science and Technology of Dielectric Films and Materials Integration for High-Frequency Devices. Orlando Auciello, Wei Fan, Bernd Kabius and Sanjib Saha; Materials Science Division, Argonne National Laboratory, Argonne, Illinois.

The science and technology of complex oxide thin films and materials integration strategies for application to high-frequency devices (HFD) will be reviewed in light of recent research that provided unique insights into fundamental and applied processes relevant to these devices, as revealed by using a variety of complementary in situ and ex situ characterization techniques. We will discuss the synthesis of BaxSr1-xTiO3 (BST) thin films and the integration with different electrode materials for application to the fabrication of capacitors for high-frequency devices such as phase array antennas. We will discuss the extensive studies performed to understand the effect of interfaces on the dielectric properties of the capacitors and the strategies developed to optimize those properties. This was achieved using a unique integrated ion beam sputter-deposition (IBSD) / in situ mass spectroscopy of recoil ions (MSRI) / X-ray photoelectron spectroscopy (XPS) system developed by our group for in situ studies of film growth and interface processes, and ex situ high-resolution HRTEM. MSRI provides atomic-scale information of species on the surface of thin films, while XPS yields information on the chemical environment at the atomic scale, HRTEM provide atomic scale information on the microstructure and composition of films and interfacial layers. We will specifically discuss recent research focused on developing robust diffusion barrier layers to integrate Cu as the electrode layer for BST capacitors. A reliable oxygen diffusion barrier is needed for integration of Cu electrodes with high-K dielectric oxide layers, since the dielectric layer of such capacitors is generally grown in an oxygen environment at relatively high temperature. For this purpose, we have investigated the integration of Ti-Al alloy layers as diffusion barriers in heterostructured Ti-Al/Cu/Ta multilayers, which exhibited exceptional thermal stability and outstanding electrical conductivity. (BaxSr1-x)TiO3 (BST) thin films were subsequently deposited on the Cu-based bottom electrode by RF magnetron sputtering to investigate the performance of BST/Cu-based capacitors for high-frequency devices. We demonstrated the first BST/Cu-based capacitors with good electrical properties that open the way for BST-based capacitors with low-loss high-conductivity electrodes for the development of GHz frequency devices. Outlook for future research will also be discussed. * This work was supported by the U.S. Department of Energy, BES-Materials Sciences, under Contract W-31-109-ENG-38.

9:00 AM G1.2
RF Magnetron Sputtered Ba0.96Ca0.04Ti0.84Zr0.16O3 Thin Films for High Frequency Applications. Ali Mahmud[1], Thottam S. Kalkur[1] and Nick Cramer[2]; [1]Electrical and Computer Engineering, University of Colorado at Colorado Springs, Colorado Springs, Colorado; [2]Applied Ceramics Research, Colorado Springs, Colorado.

Perovskite, ferroelectric and paraelectric thin films exhibit outstanding dielectric properties, even at high frequencies (>1 GHz). The non-linear electric field dependence of ferroelectric thin films can be used to design frequency and phase agile components. High dielectric constant thin film ferroelectric materials in their paraelectric state have received enormous attention due to their feasibility in applications, particularly decoupling capacitors and tunable microwave capacitors; the latter application has been fueled by the recent explosion in wireless and satellite communications. In this paper, Ba0.96Ca0.04Ti0.84Zr0.16O3 (BCTZ) thin films deposited on Pt electrodes using radio frequency magnetron sputtering at low (<450 oC) substrate temperature is discussed. RF magnetron sputtered thin film BCTZ at low substrate temperature allows this process to be compatible with current integrated circuit technology. The structural characterization of the deposited films was performed by x-ray diffraction and scanning electron microscopy. The electrical characterization of the films was determined by capacitance-voltage (C-V), current-voltage, and S-parameter measurements. In addition, the effect of post annealing on the deposited films was investigated. A detailed understanding of both their processing and material properties is discussed for successful implementation in high frequency applications.

9:15 AM G1.3
Ferroelectric Thin Films and Composites for Tunable Microwave Devices. Menka Jain[1], N. K. Karan[1], Ram S. Katiyar[1], A. S. Bhalla[2], F. A. Miranda[3] and F. W. VanKeuls[4]; [1]Department of Physics, University of Puerto Rico, San Juan, PR, Puerto Rico; [2]Materials Research Institute, The Pennsylvania State University, University Park, Pennsylvania; [3]NASA, Glenn Research Center, Cleveland, Ohio; [4]The Ohio Aerospace Institute, Cleveland, Ohio.

In the past few years, ferrolectrics have been studied for several frequency agile microwave electronic devices. Due to their tunable properties (variation of dielectric constant with applied electric field), ferroelectric materials like barium strontium titanate (BST), lead strontium titanate (PST), and strontium titanate (STO) are considered suitable for tunable microwave devices, such as phase shifters, filters, varactors, delay lines, etc. The required properties of ferroelectric thin films for such devices include, moderate dielectric constant, low dielectric losses, low leakage currents, high figure of merit (phase shift/insertion loss) etc. In the present study thin films and multilayers of BST/PST and their composites with low loss dielectrics like MgO, $MgTiO_3$ and Al_2O_3 were prepared by sol-gel technique and studied for room temperature tunable microwave devices. In addition, the effect of highly pure (99.999%) precursors on dielectric properties of these films was also studied. X-ray diffraction studies showed that the pure and composite films were highly (100) oriented on lanthanum aluminate substrates. Temperature dependent dielectric properties including dielectric constant, tunability, loss, and K factor (tunability/loss) were measured at 1MHz. For the composite films, considerable reduction in the dielectric constant and dielectric losses were observed, which translated to a moderate or high K factor. These films were used to make eight element coupled microstrip phase shifter and characterized in a frequency range of 14-17 GHz. The figure of merit was found to be markedly improved (95 ^{o}/dB for BST:MgO composite films as compared to 30 ^{o}/dB for the pure BST film). Initial studies on the PST films showed figure of merit of 56 ^{o}/dB at 15.75 GHz. Better values for the figure of merit are expected for composites and with those prepared using highly pure precursors.

9:30 AM G1.4
$Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ Thin Films for Tunable Microwave Applications. Jiwei Lu[1], Jaehoon Park[2], Nadia Pervez[2], Robert A. York[2] and Susanne Stemmer[1]; [1]Materials, University of California, Santa Barbara, California; [2]Electrical and Computer Engineering, University of California, Santa Barbara, California.

Films that combine a large tunability of their dielectric permittivity with low dielectric loss are attractive for tunable microwave device applications. Recently, $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$ (BZN) thin films with the cubic pyrochlore structure have attracted interest for integrated capacitor applications because of their relatively high permittivity (170-220) and dielectric loss tangents (tan δ) that were as low as $5x10^{-4}$. Furthermore, BZN thin films exhibit an electric field tunable dielectric constant of about 55 % at room temperature. However, bulk BZN ceramics show a low temperature dielectric relaxation that is associated with a dielectric loss peak. This loss peak shifts to higher temperatures at higher measurement frequencies, approaching room temperature in the microwave frequency region. We show that for BZN thin films, the dielectric relaxation can be shifted to lower temperatures, due to tensile stress due to the thermal mismatch with the substrate. This makes these films attractive for low-loss, high-frequency applications by extending the frequency range for which these films show low losses. The relationship between film strain and dielectric properties will be discussed. We present dielectric measurements at microwave frequencies. The total device quality factor and capacitance of planar capacitors with BZN films were analyzed by measuring scattering parameters with a vector network analyzer. The total device quality factor was greater than 200 at 1 GHz, exceeding the performance of similar capacitors using thin films of materials traditionally considered for tunable microwave applications, such as $(Ba,Sr)TiO_3$. The capacitance showed no evidence of an onset of a dielectric relaxation in the measured frequency range (1-20 GHz). The dielectric loss and constant of BZN films at microwave frequencies were modelled using measurements of test structures and appropriate equivalent circuit models to extract the influence of electrodes and parasitics.

9:45 AM G1.5
An Application of a Low-Loss MOD-Made BST Film Developed Especially with PLD Initial Nucleation Layer to a 20 GHz Tunable Phase Shifter. Minoru Noda[1], Daniel Popovici[1], Masanori Okuyama[1], Yoshinobu Sasaki[2] and Makio Komaru[2]; [1]Graduate School of Engineering Science, Osaka University, Toyonaka, Japan; [2]Semiconductor Group, Mitsubishi Electric Corporation, Itami, Japan.

We have successfully obtained a low loss $Ba_xSr_{1-x}TiO_3$ (BST) thin film on MgO substrate by combining preparation of initial layer by Pulsed Laser Deposition (PLD) and following Metal-Organic-Decomposition (MOD) method. The new preparation method enables us to use MOD method fully and successfully on various oxide insulating substrates, necessary to compose a coplanar wave guide (CPW) transmission line type of ferroelectric tunable devices in the range of microwave and millimeter wave. In this work, initial nucleation sites (1-10 nm thickness) were introduced at first on the oxide substrate by PLD, where active species of BST components ablated by laser energy can adhere to the oxide substrate surface successfully and become the nucleation sites and bonding adhesive for the following MOD growth process, making its smooth coating and improving the film crystallinity. It is considered that nucleation islands of BST are initiated by the PLD and promote crystal growth of MOD film. It is found from X-ray diffraction patterns that main orientations of BST(100) and (110) are clearly observed on MgO substrate, indicating excellent BST crystallinities. In order to design a tunable phase shifter circuit, we fabricated a series of CPW transmission line and interdigitated capacitors for obtaining effective permittivity of the CPW with the BST film dependent on applied bias, with Al(400nm) or AuCr(500nm) /MOD-made BST(x=0.6) (600nm) with the nucleation layer/MgO structure. For the interdigitated capacitors with finger spacing of 10 μm, dielectric loss was found to be as low as 0.002 to 0.004 when applied surface electric field was from -/+40 to +/-40 kV/cm at measuring frequency of 1 MHz, where tunability was about 12%. Moreover, it increases up to about 40 % in a Pt/BST/Pt stacked capacitor structure when the applied electric field was from -/+170 to +/-170 kV/cm at the same frequency. When applying dc bias voltage of 0 to 60 V to the electrodes of the CPW pattern (width:60 μm, gap:10 μm, length:2.5 mm), a differential phase shift of 18 degree was obtained at 20 GHz with insertion loss of about -2 dB for Au/Cr interconnection due to its lower resistivity. Therefore, the figure-of-merit becomes 9 degree/dB for the Au/Cr case. The measured S parameters of the CPW were found to agree well with those simulated by MicroWave Office ver.6. A 3-stage LC-ladder-type phase shifter with variable capacitors of BST film was designed by adapting the values of the mentioned effective permittivity of the CPW. The BST phase shifter is also designed to have a differential phase shift of about 40 degrees at 20 GHz and to be applied for precise phase compensation for a digital 360 degree phase shifter. A fabricated phase shifter designed above shows successfully the shift of 40 deg at 20GHz with bias of 60 V. Finally it is found that the new BST film process is very promising for realizing a micro and millimeter-wave tunable device.

10:30 AM *G1.6
Integrating $Ba_{1-x}Sr_xTiO_3$ Thin Films with Large Area, Affordable, Industry Standard Substrates for Microwave Applications. William D. Nothwang[1], M. W. Cole[1], P. C. Joshi[2], S. G. Hirsch[3], E. Ngo[1] and C. Hubbard[1]; [1]Army Research Laboratory, APG, Maryland; [2]Sharp Laboratories of America, Inc., Camas, Washington; [3]Oak Ridge Institute for Science & Education, Oak Ridge, Tennessee.

The Army is actively pursuing technologies to meet transformation goals of a lighter, faster, more lethal force via affordable, electronically scanned phased array antennas (ESA's) that will provide the means for achieving this high data rate, beyond line of sight, On The Move (OTM) communications. Paraelectric, active thin films (Magnesium doped Barium Strontium Titanate), compositionally designed for tunable microwave applications, have been deposited on ceramic (MgO, $LaAlO_3$, $SrTiO_3$, Al_2O_3) substrates. In order to transition this technology to Army applications, it is absolutely necessary that the cost of each device be decreased. By integrating this active material with large area, low cost, microwave friendly substrate, the cost can be significantly reduced. While Si is not a suitable substrate for microwave applications, a low cost, microwave friendly buffer layer on silicon would be an ideal solution. A high performance Ta_2O_5 thin film passive buffer layer on Si substrates has been successfully designed, fabricated, characterized, and optimized via metalorganic solution decomposition technique. The optimized Ta2O5 based thin film exhibited suitable microwave material properties, including an enhanced dielectric constant (ϵ' =45.6), low dielectric loss (tan δ=0.006), low leakage current or high film resistivity (ρ=10^{12} Ω-cm at E=1 MV/cm), excellent temperature stability (temperature coefficient of capacitance of 52 ppm/C), and excellent bias stability of capacitance (1.41% at 1 MV/cm). Also of extreme importance, the permittivity and dissipation factor exhibited minimal dielectric dispersion with frequency. The dielectric passive buffer layer film was typified by a uniform dense microstructure with minimal defects, and a smooth, nano-scale fine grain, crack/pinhole free surface morphology. There was negligible elemental interdiffusion with temperature at the interface between the substrate and buffer layer as verified by Rutherford Backscatter Spectroscopy and Auger insuring long-term reliability of the heterostructure. By developing a passive, thin film material that is microwave friendly, the Army Research Laboratory has enabled the direct integration of paraelectric active thin films with silicon substrates. This will allow phase shifter materials technology to be implemented across a wide spectrum of Army and Commercial applications; specifically, affordable OTM phased array antenna systems across a variety of DoD platforms will allow for a full-spectrum, network integrated theater.

11:00 AM G1.7
Y-Doping Effects on the Dielectric Behavior of RF-Sputtered BST Thin Films. Ruey-Ven Wang[1], John D. Baniecki[2], Kenji Nomura[2], Takeshi Shioga[2], Paul C. McIntyre[1] and Kazuaki Kurihara[2]; [1]Materials Science and Engineering, Stanford University, Stanford, California; [2]Fujitsu Laboratories Ltd., Atsugi, Japan.

High dielectric constant, perovskite-structure materials, such as barium strontium titanate (BST), have been widely investigated for use in GHz LSI decoupling capacitor applications. In addition to modifying deposition process parameters, such as increasing deposition temperature, doping may be a viable way to increase permittivity and tunability in BST thin films without increasing the thermal budget. In this research, the effects of Y dopants on the dielectric behavior of RF-sputtered BST thin films have been systematically investigated. The BST thin films were deposited using ceramic targets with different compositions of yttrium oxide dopant. With Y-doping concentration of 1.3 at%, the permittivity at around zero electrical fields can be increased by more than 70% compared to nominally undoped BST thin films produced under the same deposition conditions. Based on x-ray diffraction strain analysis and inductively-coupled plasma composition measurements, the correlations among the dopant composition, BST film strain and dielectric behavior have been systematically studied. Furthermore, in combination with studies of undoped reference samples with a range of Ti stoichiometries, the current understanding of possible mechanisms responsible for the increase in permittivity of Y-doped BST thin films will be discussed.

11:15 AM G1.8
ALD Ta_2O_5 and TiO_2 Buffer Layers for Integrating $(Ba,Sr)TiO_3$ Microwave Tunable Devices onto Si Wafers. Il-Doo Kim[1], Hyun-Suk Kim[2], Jin-Seong Park[3], YongWoo Choi[4] and Harry L. Tuller[1]; [1]Department of Materials Science and Engineering, MIT, Cambridge, Massachusetts; [2]Department of Materials Science and Engineering, KAIST, Daejeon, South Korea; [3]Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts; [4]Microsystem Technology Laboratory, MIT, Cambridge, Massachusetts.

$(Ba,Sr)TiO_3$ based tunable devices are usually fabricated on small area single crystal substrates such as $LaAlO_3$ and MgO due to good lattice match and low substrate dielectric loss. By replacing present bulky tuned circuits, relying on hybrid technology, with thin film elements directly integrated onto silicon chips, one reduces size and power consumption and promises improved reliability, reduced cost, and high volume production by use of large size Si wafers. However, crack formation, high surface roughness due to chemical reactivity and large lattice mismatch between BST and Si make it very difficult to grow BST films directly onto Si. In addition, high microwave losses related to the low resistivity of Si is also a barrier for integration of BST devices onto Si wafers. To solve these problems, we introduced suitable buffer layers, with high dielectric constant, between the BST layers and the Si substrate. The buffer layers have multiple purposes including serving as templates for high quality BST growth, providing stress control for crack-free films, preventing chemical reactions and providing electrical isolation,. We will describe the ALD (Atomic Layer Deposition) of Ta_2O_5 and TiO_2 buffer layers and their effect on the improvement of tunability of $Ba_{0.6}Sr_{0.4}TiO_3$ microwave tunable devices. The TiO_2 and Ta_2O_5 buffer layers were grown on Si wafers and annealed at 700^{o}C and 800^{o}C for 30 min, respectively. Perovskite $Ba_{0.6}Sr_{0.4}TiO_3$ thin films were deposited on the Ta_2O_5/Si or TiO_2/Si substrate by pulsed laser deposition (PLD). The BST films on the TiO_2/Si substrate were found to be more randomly oriented and showed a larger grain size distribution compared to that on theTa_2O_5/Si substrate, on which the BST film was found to be highly (110) textured. At an applied voltage of 10 V, the tunability of the BST films grown on Ta_2O_5/Si and TiO_2/Si substrates were 72.9% and 53.1%, respectively, values much larger than that (17.9%) of BST films grown on a MgO single crystal substrate. BST films grown on GaAs and high resistivity Si substrates will be characterized in terms of tunability and microwave loss and compared with the BST film on the bufferd Si substrates. In summary, ALD grown Ta_2O_5 and TiO_2 buffer layers enable successful integration of BST based microwave tunable devices onto Si wafers.

11:30 AM G1.9
Growth and Characterization of Degradation-Free c-Axis-Oriented $(Ca_x, Sr_{1-x})Bi_4Ti_4O_{15}$ Thin-Film Capacitors. Kenji Takahashi[1], Shoji Okamoto[1], Yukio Sakashita[2], Haydn Chen[3] and Hiroshi Funakubo[1,4]; [1]Tokyo Institute of Technology, Yokohama, Japan; [2]TDK Corporation, Chiba, Japan; [3]City University of Hong Kong, Kowloon, Hong Kong; [4]Japan Science and Technology Agency, Saitama, Japan.

High-dielectric constant materials with good stability against the applied electric field, film thickness and the temperature are highly desired for various capacitor applications. We have previously proposed that *c*-axis-oriented bismuth layer-structured dielectric (BLD) films are a novel candidate for high dielectric capacitor application due to the low capacitance change against the applied voltage and the low leakage current independent of the film thickness down to 20 nm together with the smooth surface.[1)] In addition, these are promising candidates for the microwave devices because of their high dielectric constants, low losses and tailored temperature coefficients of dielectric constant.[2)] However, previous studies were concentrated on the epitaxial films grown on single crystal substrates. In order for these films to receive wider applications, the establishment of deposition method of *c*-axis-oriented BLD films on various substrates is critical. In the present study, we have successfully prepared a single axis, *i.e.* *c*-axis oriented BLD films even on the (111)Pt/TiO_2/SiO_2/Si polycrystalline substrates by inserting the (001)-oriented $LaNiO_3$ conductive buffer layer as an interfacial template. A comparison of the dielectric properties of these films was made with epitaxial-grown films in the viewpoint of in-plane and out-of-plane orientations. $CaBi_4Ti_4O_{15}$ (CBTi) films with various thickness were deposited on $LaNiO_3$ buffered (111)Pt/TiO_2/SiO_2/Si substrates at 600°C by rf magnetron sputtering deposition. Without the $LaNiO_3$ buffer layer, CBTi films showed random orientations. However, with the $LaNiO_3$ buffer layer, which showed preferred (001)-orientation characteristic even on (111)Pt, CBTi films were found to show an out-of-plane *c*-axis but in-plane random orientations. Furthermore, the crystallinity of CBTi films was improved by adding an additional layer of conductive (001)-oriented $SrRuO_3$ between CBTi film and $LaNiO_3$ layer. It was demonstrated that the general observation of degradation of dielectric constant with decreasing thickness was not seen for CBTi films on all substrates. In fact these films behave in a similar manner to those epitaxial CBTi films grown on (001)$SrRuO_3$//(001)$SrTiO_3$ substrates. Our results clearly demonstrated that a single axis *c*-oriented CBTi films yield no degradation of dielectric properties against the film thickness, thus making them highly desirable for new capacitor application. These capacitors can be made not only on Si substrates but also on other substrates, such as metal plates, glass and resin. [1)] T. Kojima *etal.*, Mater. Res. Soc. Symp. Proc. 748, U15.2.1 (2003). [2)] S. Kojima *etal.*, Anal. Sci. 17, i681 (2001).

11:45 AM G1.10
AC Loss Modeling in $Ba_{0.5}Sr_{0.5}TiO_3$ Using Dielectric Relaxation. Nadia K. Pervez[1], Jiwei Lu[2], Susanne Stemmer[2] and Robert A. York[1]; [1]Electrical and Computer Engineering, University of California, Santa Barbara, California; [2]Materials Department, University of California, Santa Barbara, California.

Universal relaxation refers to behavior where a material's complex dielectric susceptibility is observed to follow a decreasing power law over multiple decades in frequency [1]. This behavior is observed in a variety of different materials including $Ba_xSr_{1-x}TiO_3$, Al_2O_3, Ta_2O_5, HfO_2, and SiO_2 [2,3]. It appears to be a property of extrinsic disorder rather than an intrinsic material property [4,5]. The susceptibility shows an f^{1-n} frequency dependence, where $0 < n < 1$. For a lossless material, n = 1. A direct consequence of this power law is that if the real component of a material's complex susceptibility obeys a power law, so must the imaginary component. While many materials have been observed to obey Curie-von Schweidler behavior, corresponding to n 1, little attention has been focused on the corresponding loss predictions using the universal relaxation model. Even when little relaxation is observed – when n is very close to 1 – the model can still accurately predict loss. The ability to calculate losses from capacitance data may be advantageous in situations where the direct measurement of Q-factors is difficult, such as network analyzer measurements of low-loss films. Reflection-type measurements of high-Q reactive loads performed with network analyzers are less accurate than auto-balancing bridge measurements performed with impedance analyzers. However, auto-balancing bridge measurements are limited to below 110 MHz. Provided that parasitic electrode inductances at high frequencies can be accounted for, this technique offers an accurate way to indirectly measure film loss through capacitance measurements. In $Ba_{0.5}Sr_{0.5}TiO_3$ we have successfully used power-law capacitance data to predict Q-factor values. Table 1 shows a comparison between 1 MHz Q-factors calculated and measured using an impedance analyzer. The calculated values are consistently equal to or slighter higher than measured values, consistent with the expected small contribution of series electrode resistance to measured Q-factors at 1MHz. [1]A.K. Jonscher, J. Phys.D: Appl. Phys., 32, R57-R70 (1999). [2]J. D. Baniecki, et al., Appl. Phys. Lett., 72, 498-500 (1998). [2]H. Reisinger, et al., IEDM Tech. Digest, 12.2.1-4 (2001). [3]D.P. Almond, and C.R. Brown, Phys. Rev. Lett. 92, 157601-1 (2004). [4]J.R. Jameson, W. Harrison, P.B. Griffin, and J.D. Plummer, Appl. Phys. Lett. 84, 3489 (2004).

SESSION G2: Resonators and Measurement
Chairs: William Borland and Takaaki Tsurumi
Monday Afternoon, November 29, 2004
Liberty (Sheraton)

1:30 PM *G2.1
Thin film BAW resonators based on AlN: remaining challenges in film growth. Paul Muralt, Ceramics Laboratory, EPFL, Lausanne, Switzerland.

Very recently, bulk acoustic wave (BAW) filters based on AlN thin films have emerged as promising components to compete with SAW products in rf filtering. The commercial products target especially at the frequency bands around 2 GHz for mobile communication and 2.5 and 5 GHz for local area networks. At these high frequencies, BAW filters exhibit advantages with respect to fabrication, power limits, and parasitics. TFBARS look also very suitable for advanced integration leading to shrinkage of volume and number of components in mobile phones. AlN can be readily introduced into semiconductor fabrication lines. There are thus many plans to implement above chip resonators for filters, oscillators, and channel selection. The crucial factor in BAW devices is the control of AlN film thickness and properties. The paper will give an overview of the current state of the art in AlN processing and film properties. The films are grown by reactive magnetron sputtering at relatively low temperatures of 100 to 400 degrees Celsius. Ion bombardment is the main driving mechanism to achieve polar films at such low temperatures. All our knowledge on piezoelectric properties originates from experiments on thin films. Over the last years, film quality has improved resulting in higher piezoelectric coefficients than expected. The crucial part of growth is the nucleation of (001) grains of uniform polar direction. A further parameter is the flatness of the substrate (rocking curve width). Even if it is clear that ion-bombardment and adatom mobility play a role, the exact mechanisms are still not elucidated yet. Chemical nature of the surface as well as the impedance of the substrate in the pulse discharge may play a role. While the fabrication of simple electrode-AlN-electrode structures seems to be a solved problem, even though involving a lot of work in improving electrodes, the re-growth of AlN as needed for double frequency operation is still a challenging topic.

2:00 PM G2.2
Pulsed DC Sputtered Aluminum Nitride : A Novel Approach to Control Stress and C-Axis Orientation. Philippe Soussan[1], Kathy O'Donnell[2], Wanling Pan[1], Jan D'Haen[3], Geert Vanhoyland[4], Eric Beyne[1] and Harrie A. C. Tilmans[1]; [1]Microsystems , components and packaging, IMEC, Heverlee, Belgium; [2]Nexx systems, Billerica, Massachusetts; [3]IMOMEC, IMEC, Diepenbeek, Belgium; [4]Institute for Material research, Limburgs Universitair centrum, Diepenbeek, Belgium.

For application in high frequency devices like film bulk acoustic resonators (FBARs) thin-film piezoelectric aluminum nitride (AlN) must display perfect c-axis orientation (going along with a high piezoelectricity) and a low residual film stress. Recently, significant improvements were reported for deposition on Platinum [1]. By comparison and despite its economical interest, deposition processes on Aluminum remain challenging because the AlN film deposited on it presents poorer properties [2]. This paper reports on a novel low temperature sputter deposition process yielding films with stresses and crystalline orientation on Al comparable to Pt. The study focuses on the importance of the initial film growth step on both stress and crystalline orientation. The AlN layer is deposited using Pulsed DC (250 kHz, 90% duty cycle) magnetron reactive sputtering (93% N2, 7% Ar) using an Al target. The substrates are 150mm Si wafers coated with an aluminum thin film. The thickness of the AlN films is about 2.5μm with a uniformity across the wafer of 0.4%. The films have been deposited in 4 passes of 0.625μm each to avoid overheating of the substrate. An interesting additional factor is the fact that for each pass the deposition conditions may be different. The influence of the RF substrate bias (0, 80 and 120V, integrated value from power) and argon pre-sputtering (present or not) of the aluminum have been investigated. The gas flow, plasma pressure and power were kept constant. Full Width at Half Maximum of the rocking curve of the (0002) plane is used to quantify cristallinity of layers and wafer bow measurements are used to quantify the stress of the films. The films grown on an aluminum layer with 0V bias exhibit a FWHM rocking curve angle of 2.8° but displayed cracks due to a large tensile stress, exceeding 1.1GPa. For the films having their first layer deposited using a DC bias of 80V and 120V, it was found, that the stress and, to a smaller extent, the crystalline orientation of the remaining 3 layers showed only a small dependence on the substrate bias during deposition. For the films deposited using a DC bias of 120V, the impact of the argon pre-sputtering on the first layer is visible with a change from compressive w/o pre-sputtering towards tensile stress with pre-sputtering. It can be concluded that, within a certain range, the deposition parameters during the initial film growth are driving the properties of the total film. A possible explanation for this drasting dependence is the difference in the seed layer. Lattice mismatch (in this case fcc pattern of (111) Al towards hexagonal crystal structure of AlN), inertness to nitrogen, activation of the surface, are known to have an impact on the quality of the film. With this method, it was possible to deposit AlN layers on Al with a FWHM of the rocking curve of 2.45° and low stress (<300MPa). [1] Martin, JVST A, 2004, p361 [2] Naik, J Elec Soc, 1999, p691

2:15 PM G2.3
Epitaxial Growth of Pulse Laser Deposited AlN Films for MEMS and NEMS Based RF Resonators : Technical Barriers and Solutions. Shiva Hullavarad[1], R. D. Vispute[1,3], T. Venkatesan[1], A. E. Wickenden[2], L. Currano[2] and M. Dubey[2]; [1]Center for Superconductivity Research, University of Maryland, College Park, Maryland; [2]Army Research Laboratory, Adelphi, Maryland; [3]BlueWave Semiconductors, Inc, Baltimore, Maryland.

AlN exhibits strong piezo-electric properties suitable for RF resonator applications. In this work we report the growth of highly oriented AlN films for MEMS and NEMS resonator devices. A multiple flexural structure of Pt/SiO2/Si is used as a substrate and films are grown by Pulse Laser Deposition (PLD) technique at a pulse energy of 2J/cme2 with a repetition rate of 10 Hz. The process is optimized for the growth of AlN on different thicknesses of underlying SiO2. The films are characterized by XRD, RBS and techniques for crystalline quality and stoichiometry respectively. The interface analysis of underlying structures is analyzed in detail by RBS and oxygen content in the film is monitored by Resonant Oxygen Scattering technique. The morphology of AlN films is studied by scanning electron and atomic force microscopies. We have obtained highest Q factors for PLD grown AlN MEMS resonator beams of Q = 8,000 at fo = 2.5 MHz and Q = 17,400 at fo = 0.44 MHz We also address in this work critical issues related to (1) thickness of SiO2 (2) method of growth of SiO2 in fabricating MEMS and NEMS devices. These factors are very essential for the growth of high quality AlN films. However, SiO2 provides a amorphous underlayer for the growth of AlN leading to non in plane aligned AlN with respect to substrate. A lattice matching, epitaxial oxide layer like Y2O3 in place of SiO2 is going to be a unique solution for eventual epitaxial growth of AlN. We address the epitaxial issues of AlN and underlying oxide for improving the resonator properties of AlN based MEMS and NEMS devices.

3:00 PM *G2.4
Microwave Materials with High Q and Low Dielectric Constant for Wireless Communications. Hitoshi Ohsato, Material Science and Engineering, Nagoya Institute of Technology, Nagoya, Japan.

The wireless communications have been tremendously developed in recent ubiquitous age. The utilizable region for the frequency expands to millimeterwave, because of shortage of the region. The high frequency would be expected for ultra high speed LAN, ETS and car anti-collision system on the intelligent transport system (ITS) and so on. In this paper, microwave dielectric ceramics for ultra high frequency are mainly stated, and compared with Surface Acoustic Wave (SAW) and Film Bulk Acoustic Resonator (FBAR) filter. There are three main properties: dielectric constant (ϵr), quality factor (Qf) and temperature coefficient of microwave dielectrics (τf). The dielectrics for ultra high frequency are expected being low ϵr and high Qf. The candidates for millimeterwave are silicates such as forsterite and willemite, and corundum group compounds such as alumina and Mg4(Nb2-xTax)O9, and green phases such as Y2Ba(Cu1/4Zn3/4)O5. High purity forsterite has low ϵr of 7.0 high Qf of 270,000GHz and τf of -65ppm/°C. Moreover, rutile added forsterite has zero ppm/°C τf with ϵr of 11, and Qf of 85,000GHz. Willemite also has low ϵr of 6.5, and high Qf of 160,000GHz. Alumina has ultra high Qf of 680,000GHz with ϵr of 10.05, and τf of -60 ppm/°C. Moreover, rutile added alumina has also near-zero τf (1.5 ppm/°C) with ϵr of 12.4, and Qf of 117,000GHz. Mg4(Nb2-xTax)O9 belong to corundum group has ϵr of 11.5, Qf of 350,000 GHz, and τf of -70ppm/°C. Y2Ba(Cu1/4Zn3/4)O5 belong to green phase group has ϵr of 15.4, Qf of 220,000 GHz.

3:30 PM G2.5
Structural and Dielectric Properties of New Ordered Niobate Perovskites. Hui Wu and Peter K. Davies; Materials Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania.

Ceramics based on Ba(Zn1/3Nb2/3)O3 (BZN) have been extensively investigated for application as microwave dielectric resonators in wireless communications systems. Because the B-site ordering transition of BZN (1375oC) lies below the temperatures used in sintering (1450oC), the limited thermal stability of the high Q (low dielectric loss) ordered phase impedes the design of a suitable route to optimize the microwave dielectric properties. The processing is also complicated by the volatility of ZnO at high temperature. This work has investigated new methods for stabilizing the order and lowering the sintering temperature of BZN through the partial substitution of tungstate-based perovskite additives. Examples include solid solutions such as [(1-x)Ba3ZnNb2O9-(x)Ba3W2O9] and [(1-x)Ba3ZnNb2O9-(x)Ba3WVO8.5]. In these systems the incorporation of very small concentrations of vacancies on the B-site, compensated by the partial replacement of Nb by W, increases the ordering temperature of BZN and dramatically enhances the kinetics of the B-site ordering reaction. For example, in a composition containing 1 mole Ba3W2O9 the ordering phase is stable up to 1410oC; this substitution also reduces the sintering temperature by as much as 50oC. The ceramic samples of these solid solutions exhibit some of the lowest dielectric losses recorded for niobate perovskite dielectrics with Q.f's > 110,000 at 8 GHz. The role of B-site vacancies and W on the sintering, microstructure and stabilization of the cation ordering will be discussed together with the correlations between the phase stability and microwave dielectric properties.

3:45 PM G2.6
Microwave Dielectric Properties and Crystal Chemistry of $Ba_3MNb_{2-x}Sb_xO_9$ (M = Mg, Ni, Zn). Michael Wayne Lufaso[1], Steve M. Bell[2] and Elizabeth A. Hopkins[1]; [1]Ceramics Division, National Institute of Standards and Technology, Gaithersburg, Maryland; [2]TCI Ceramics, Hagerstown, Maryland.

Exceptional microwave dielectric properties are exhibited by $Ba_3ZnTa_2O_9$ and $Ba_3MgTa_2O_9$, which are members of the of 2:1 ordered perovskite structure class. Substitution of Nb^{5+} for Ta^{5+} results in isostructural compositions with a higher dielectric constant, more positive temperature coefficient of resonant frequency, and a smaller Q×f value. Diminished dielectric properties have prevented to the use of the Nb^{5+} perovskites as replacements for the Ta^{5+} perovskites, even though the lower material cost, higher dielectric constant, and lower processing temperatures make Nb^{5+} perovskites attractive. Substitution of Sb^{5+} for Nb^{5+} was performed to examine the influence on both the crystal structure and dielectric properties. Significant differences in the crystal structures are observed because of the size and electronic differences of the d^{10} Sb^{5+} compared to the d^0 Nb^{5+}. Solid solutions form for each end member structure type and a two-phase mixture region forms in between. The crystal phase(s) and dielectric properties may be altered by appropriate substitution of Sb^{5+} and the divalent B-site cation. Dielectric constants, temperature coefficients of resonant frequency, and Q×f are presented versus Sb^{5+} substitution.

4:00 PM G2.7
Low Temperature Crystallization of MOD Gorwn Bismuth Zinc Niobate Thin Films Using Excimer Laser Treatment. Jian-Gong Cheng and Susan Trolier-McKinstry; Materials Research Institute and Materials Science and Engineering Department, Penn State University, University Park, Pennsylvania.

The rapid development of communication technologies, especially mobile communication systems, is facilitated by miniaturization of devices. Integrated decoupling capacitors and microwave resonatores are of interest for such systems. Dielectric materials for these applications must possess medium or high permittivity, low temperature coefficients of capacitance (TCCs) and low loss tangent values. For this purpose, bismuth zinc niobate (BZN) thin films with different composition have been studied, and it has been demonstrated that $Bi_{1.5}Zn_{1.0}Nb_{1.5}O_7$, $Bi_{1.5}Zn_{0.5}Nb_{1.5}O_{6.5}$, and $Bi_2Zn_{2/3}Nb_{4/3}O_7$ films deposited by metalorganic decomposition (MOD) methods have many of the required electrical properties[1, 2, 3]. However, typically, the annealing temperature must be higher than 650 °C to get well crystallied BZN films, which makes integration with polymeric substrates problematic. To reduce the annealing temperature, pulsed laser annealing (PLA) was employed using a defocused 248 nm laser beam. Well crystallized $Bi_{1.5}Zn_{0.5}Nb_{1.5}O_{6.5}$ films have been successfully obtained by PLA at a laser energy density of 34 mJ/cm^2 and substrate temperatures around 400 °C. Electrical measurements showed that the PLA $Bi_{1.5}Zn_{0.5}Nb_{1.5}O_{6.5}$ films (laser energy of 34 mJ/cm^2, Tsub = 400°C) have a relative permittivity as high as 178, with low loss tangents and a TCC of -285 ppm/°C. The dielectric constant of the PLA $Bi_{1.5}Zn_{0.5}Nb_{1.5}O_{6.5}$ films decreased with bias field, while the loss tangent changed very very little. The dielectric constant changed 5% under a bias of 676 KV/cm; a higher tunability is expected when higher bias is applied to the samples. The dielectric properties of the PLA $Bi_{1.5}Zn_{0.5}Nb_{1.5}O_{6.5}$ films annealed at 400 °C are comparable to those of RTA $Bi_{1.5}Zn_{0.5}Nb_{1.5}O_{6.5}$ films annealed at 650 °C. The low annealing temperature with PLA technique make integration with polymeric substrates possible; results of studies towards this will be reported. References 1. Wei Ren, Susan Trolier-Mckinstry, Clive A. Randall and Thomas R. Shrout, J. Appl. Phys. 89, 767 (2001). 2. R. L. Thayer, C. A. Randall, and S. Troler-Mckinstry, J. Appl. Phys. 94, 1941 (2003). 3. Jiwei Lu and Susanne Stemmer, Appl. Phys. Lett. 83, 2411 (2003).

4:15 PM *G2.8

Precision Measurement of Low Loss Window Materials. Jyotsnamoy Dutta and Charles Ron Jones; Physics, NC Central University, Durham, North Carolina.

A precision measurement technique for measuring complex dielectric permittivity in the 118 to 178 GHz frequency range is suggested. The combination of high-quality Fabry-Perot resonator, excited by BWO-generator (without any phase lock system), with the great processing capability of a sensitive receiver based on the Tektronix 2782 spectrum analyzer, using the WM782 (F-G) harmonic mixer, opens the possibility of a new measuring technique. Electron Cyclotron Waves (ECW) systems operating in the millimeter wave (mm-wave) spectral region are often utilized in fusion devices to provide a well-localized energy deposition for building-up and controlling burning plasma. The growing use of such systems in plasma experiments requires gyrotron tubes capable of producing CW power of 1 MW or more in the frequency range of 110-200 GHz. In gyrotron tubes, the radio frequency window forms a critical component, as it must not only provide a vacuum barrier but also a tritium barrier between the plasma chamber and its surroundings. CVD-diamond appears to have the essential properties of strength, thermal conductivity, and low absorption loss to solve the problem of megawatt output windows for gyrotrons. However, it has been observed that very substantial increases in absorption may occur during window fabrication, due to the formation of lossy surface layers. Open resonator measurement systems currently in use for loss measurements can be adapted to distinguish between these surface losses and the bulk loss, although such measurements place greater demands on system performance. Enhancements used to improve system performance will be described and results obtained on samples of CVD-diamond, with and without lossy surface layers, will be reported.

SESSION G3: Poster Session
Chairs: Yong S. Cho and Don Shiffler
Monday Evening, November 29, 2004
8:00 PM
Exhibition Hall D (Hynes)

G3.1

Improvement of Adhesion and Microwave Transmission Characteristics of Indium Bump by Silver Coating for Low Temperature Flip-Chip Applications. Kun-Mo Chu[1], Jung-Hwan Choi[2], Jung-Sub Lee[1], Han Seo Cho[2], Hyo-Hoon Park[2] and Duk Young Jeon[1]; [1]Materials Science & Engineering, Korea Advanced Institute of Science and Technology, Daejeon, South Korea; [2]School of engineering, Information and Communications University, Daejeon, South Korea.

We have conducted low-temperature flip-chip bonding for optical interconnect and microwave applications. Flip-chip bonding of vertical-cavity surface-emitting laser (VCSEL) arrays was performed on a fused silica substrate that provides propagation paths of laser beams and also supports a polymeric waveguide. To avoid thermal damage of polymeric waveguide during the flip-chip bonding, indium solder bumps are used and the bonding condition of flip-chip was determined as a heating temperature of 150°C and a pressure of 500 gf. The samples flip-chip bonded below bonding temperature of 150°C show fractures between the indium solder bump and the VCSEL chip pad during the die shear test. It is inferred that both the low bonding temperature that is lower than the melting temperature of indium and the oxide layer that is formed on the surface of the indium solder prevented the bump from interacting with the chip pad. To decrease the melting temperature of the indium solder and protect it from oxidation without using flux, we tried coating of a thin silver layer (0.2 μm) onto the indium surface by thermal evaporator. To estimate the silver coating effect, current-voltage and light-current characteristics of flip-chip bonded VCSEL arrays using silver coated indium bump compared with the samples using indium bump only. The characteristics of microwave signal transmission were performed with on-wafer probes for a frequency range extending to 40 GHz. As a result, the thin silver layer coated on the solder bump was very effective to enhance the adhesion strength between the indium bump and the VCSEL chip pads by decreasing the melting temperature of the indium solder bump locally and preventing indium surface from oxidation. In addition, the optoelectronic and microwave characteristics of VCSEL array was improved by silver coating.

G3.2

Epitaxial Aluminum Electrodes on Theta Rotated Y-X $LiTaO_3$ Piezoelectric Substrate for High Power Durable SAW Duplexers. Osamu Nakagawara, Hironori Suzuki, Shuji Yamato, Masayuki Hasegawa and Hideharu Ieki; Murata Manufacturing Co., Ltd., Kyoto, Japan.

High power durable electrodes have been successfully grown on Y-X $LiTaO_3$ piezoelectric substrates adopting epitaxial aluminum(Al) films. We have reported epitaxial Al films on Y-X $LiNbO_3$ with titanium intermediate layer in our previous paper[1)]. Despite a quite similar crystal structure, it has been difficult to form epitaxial Al on $LiTaO_3$ due to the different cut angle suitable for SAW devices. We found that a two-step process sequence in the deposition temperature of Ti intermediate layer could make it possible for Al/Ti structure to grow epitaxially on theta rotated Y-X $LiTaO_3$. What is most important for epitaxial growth is to deposit an initial region at high temperature to obtain highly oriented Ti at the interface against the substrate. Following with a low temperature process in a later stage of Ti and all the period of Al, epitaxially layered structure was completely set up. The two-step sequence of Ti can prevent inter-diffusion between Al and Ti and oxidation of Ti surface, both of which frustrate the crystal growth of Al. Crystallinity analysis was carried out by pole figure of x-ray diffraction in Al (200) incident direction. Clear symmetrical spots were observed in films prepared by the two-step process sequence, which suggests a twin crystal structure of the Al film. The best result was achieved at substrate temperature of 180 centigrade for the initial Ti region. Ladder-type SAW filters were fabricated by reactive ion etching of Al/Ti with the center frequency of 800MHz for CDMA800(AMPS). Both step-up and acceleration tests were carried out to elucidate power durability defined by 2 MHz degradation of band width among frequencies where the insertion loss goes down by 2.4 dB. Duplexers with epitaxial electrodes have had above 6 W breakdown power measured from step-up test, while those with polycrystalline electrode, 3.4 W. It was also turned out from acceleration test at input power of 3.0 W and in an ambient temperature of 85 centigrade that lifetime of epitaxial SAW was several orders longer than that of polycrystalline SAW. Epitaxial electrodes with extremely less grain boundary can improve power durability because self-diffusion of Al atoms occurs mainly in the grain boundary of the film. Interdigital transducers composed of the epitaxial Al on Y-X $LiTaO_3$ will be promising for CDMA800 antenna duplexer application in which high durability is strictly needed. 1) O. Nakagawara et al., J. Crystal Growth **249**, 497 (2003).

G3.3

Comparison of Microwave Dielectric Behavior between $Bi_{1.5}Zn_{0.92}Nb_{1.5}O_{6.92}$ and $Bi_{1.5}ZnNb_{1.5}O_7$. Wei-Fang Su[1], Ming-Chung Wu[1] and Stanislav Kamba[2]; [1]Department of Materials Science and Engineering, National Taiwan University, Taipei, Taiwan; [2]Department of Dielectrics, Institute of Physics, ASCR, Praha, Czech Republic.

Bi_2O_3-ZnO-Nb_2O_5 (BZN) system has been considered as candidate microwave materials due to their low sintering temperature, high dielectric constant and low temperature coefficient of resonance frequency. However, $Bi_{1.5}ZnNb_{1.5}O_7$ exhibits low temperature dielectric relaxation behavior which results in low quality factor of microwave property (Nino et. al, J. Appl. Phys., 2001, 89, 4512-4516). Levin et al. (J. Solid State Chemistry, 2002, 168, 69-75) investigated the structure of $Bi_{1.5}ZnNb_{1.5}O_7$ that consisted of unusual cubic pyrochore-single phase with the composition of $Bi_{1.5}Zn_{0.92}Nb_{1.5}O_{6.92}$ and small amounts of ZnO. In order to find the structural origin of the dielectric relaxation of $Bi_{1.5}ZnNb_{1.5}O_7$, we have studied the dielectric behaviors of $Bi_{1.5}Zn_{0.92}Nb_{1.5}O_{6.92}$ and $Bi_{1.5}ZnNb_{1.5}O_7$ in detail using Impedance Analyzer, Network Analyzer, and Fourier transform spectrometer. The low temperature dielectric relaxation behavior of $Bi_{1.5}ZnNb_{1.5}O_7$ was from the unusual structure of $Bi_{1.5}Zn_{0.92}Nb_{1.5}O_{6.92}$. In $Bi_{1.5}Zn_{0.92}Nb_{1.5}O_{6.92}$, 21% of Bi^{3+} atoms are replaced with Zn^{2+} atoms and 4% of the A position remains vacant that provides room for dielectric relaxation. The presence of ZnO phase in the $Bi_{1.5}ZnNb_{1.5}O_7$ further enhanced the dielectric relaxation with reduced quality factor.

G3.4

Ferromagnetic Nanoparticle/Polyurethane Nanocomposites for RF Applications. Christy R. Vestal[1], Heather Dowty[2] and Max D. Alexander[2]; [1]Universal Technology Corporation, Dayton, Ohio; [2]Air Force Research Laboratory, Wright-Patterson AFB, Ohio.

Signal conditioning devices for use in rf detection and communication applications require the development of materials with high microwave permeability and low dielectric loss in order to be suitable for use at higher frequencies. Ferromagnetic materials have high permeability, however, their use is limited due to their high conductivities and thin microwave penetration depth. One approach taken to overcome these limitations is to disperse ferromagnetic inclusions into a dielectric matrix. At least one dimension of the inclusions must be on the nanoscale so that the microwave penetrates the material. We report the synthesis of polyurethane nanocomposites containing ferrites and garnet nanoparticles with variable composition and loadings. The evaluation of the magnetic and dielectric properties of the nanocomposites will also be presented.

G3.5
Mixed-Signal Three Dimensional Integration with Benzocyclobutene as the Wafer Bonding Medium.
Sang Kevin Kim, Lei Xue and Sandip Tiwari; Cornell University, Ithaca, New York.

We report a successful three-dimensional integration technique targeted for mixed-signal, high frequency circuit integration using Benzocyclobutene as the bonding medium between device layers. The technique involves wafer scale integration of sub-micron thick RF device layer and transplanting it to a fully fabricated host wafer with digital circuits. BCB's low dielectric constant ($\epsilon r = 2.65$), low loss at high frequency and good thermal/mechanical stability allows fabrication of high performance RF components on donor device layer, which sits on top of the BCB film. Another important property of BCB is that it allows for void free device layer to layer bonding. A brief summary of the process is as follows - a fully processed SOI wafer with RF devices is temporarily bonded to a glass handling wafer with releasable adhesive. Then the entire silicon substrate of the SOI is etched, stopping on the buried oxide (BOX) of the SOI, which leaves a transparent sub-micron thick device layer or "donor layer" temporarily bonded to the glass handling wafer. The host wafer with completed digital circuits is prepared for 3D integration by spinning BCB on to it after application of proper adhesion promoter. The solvents in BCB are released in pre-bake process. Then, a contact aligner is used to align the transparent donor layer to the host wafer and the aligned stack is bonded in vacuum. The newly bonded donor/host wafer stack is subjected to a temperature of 330C - while BCB cures to make the bond between the layers permanent, the glass handling wafer is released due to depolymerization of the temporary adhesive. The BCB film, which bonds the two device layers, etches readily in SF6/O2 chemistry, allowing interconnection between the RF donor layer to the digital host layer in simple metal evaporation step. The electrical measurements of devices on the donor layer before and after transplantation step have been obtained. Detailed BCB property and processing step will be presented. The donor layer to host wafer alignment registration of +/- 3 micron was observed. We have also shown that by fabricating a ground plane between the device layers, significant amount of crosstalk to the RF donor layer from the digital host layer can be reduced.

G3.6
Design and Fabrication of Large Array, Micron Scale, Mass Analysis Systems Running at RF Frequencies.
James Fleming[1], Matthew G. Blain[1], Dolores Cruz[1], R. Graham Cooks[2], A. Guymon[2] and Daniel Austin[1]; [1]Sandia Nat Labs, Albuquerque, New Mexico; [2]Purdue University, West Lafayette, Indiana.

There is currently a great need for accurate, miniature and inexpensive detection systems for unknown chemical and biological species. Mass spectroscopy is recognized as being a highly desirable approach to this problem, but typical mass spectroscopic systems have large ion traps and operate at high vacuum, which prevents their miniaturization. This is due not just to the size of the trap, but also to the size of the vacuum pump. However, if the size of the ion trap could be greatly reduced from the centimeter scale to the micron scale then the vacuum requirements would also be relaxed to the point where miniaturization may become possible. In such a configuration, it then becomes necessary to recover sensitivity through the use of large arrays of micro-traps. What is of interest to this symposium is that the functioning of such devices will require the megahertz modulation of relatively large voltage swings. Cylindrical micro-traps have been modeled and it is predicted that trapping is possible. These structures are highly complex on the micron scale, having at least four separate, addressable electrode layers. This places considerable restrictions on the fabrication possibilities. It is possible to use polysilicon micromachining techniques to fabricate many of the complex structures required, however, polysilicon is too resistive to be viable. Aluminum has been used to successfully fabricate micromachined devices, however the vertical dimensions required here exceed those typically used in aluminum micromachining. To address this problem we have employed a micro-molded tungsten process to successfully fabricate the required structures and modeling indicates that the losses associated with these geometries and this material should be manageable. This is due to the relatively low resistivity of tungsten and the use of air bridges in the design to minimize capacitive coupling. Testing of these novel structures is currently underway. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

G3.7
Prevention of InP/InGaAs/InP Double Heterojunction Bipolar Transistors from Current Gain Reduction during Passivation.
Byoung-Gue Min, Jong-Min Lee, Seong-Il Kim, Chul-Won Ju and Kyung-Ho Lee; InP IC Team, Electronics and Telecommunications Research Institute, Daejeon, South Korea.

When the device geometry is scaled down to improve the performance, the current gain of hetero-junction bipolar transistor (HBT) is strongly influenced by the surface recombination effect. The high doped p-type base layer has high surface recombination velocity. The surface recombination on the extrinsic base region around the emitter mesa perimeter significantly degrades the current gain of the device. The devices used in this work were grown by molecular beam epitaxy (MBE) on semi-insulating (100) InP substrate. Si and C were used as the n- and p- type dopants, respectively. The devices were fabricated by using triple-mesa isolation structure. One of the epi-structures consists of InP-emitter layer on InGaAs-base layer forming an abrupt junction. In this device, the passivated surfaces are a side wall of InP emitter mesa and the surface of the high doped extrinsic p-type InGaAs base layer. On the other epi-structure with InGaAs / InAlAs emitter-base graded layers, the low doped n-type InGaAs layer is revealed to the surface. Three kinds of dielectric films for passivation were examined. Silicon nitride and silicon oxide films were deposited by plasma-enhanced chemical-vapor deposition (PECVD). The other was aluminum oxide film grown by atomic layer deposition (ALD) at lower temperature. A significant degradation of current gain of the InP / InGaAs / InP double hetero-junction bipolar transistors was observed after passivation. The degradation of current gain is mainly caused by large increase of the base forward leakage current. The amount of degradation depended on the surface exposure of the p-type InGaAs base layer resulting in different behavior according to the epi-structures and the device configuration. A drastic gain reduction is observed at the device fabricated from epi-wafers with abrupt junction, but any difference of current gain was not observed in case of the device with emitter-base graded layer. The deposition conditions such as deposition temperature, kinds of passivating materials and film thickness were not major variables to affect the device performance. The gain reduction was prevented by the BOE (buffered oxide etcher) treatment before the passivation process. A possible explanation of this behavior is that unstable non-stoichiometric surface states produced by excess In, Ga, or As after mesa etching are eliminated by BOE treatment. The self-aligned HBT was successfully fabricated utilizing crystallographic anisotropy of mesa profiles by wet etching. The device with emitter size of 0.8 x 6 μm^2 showed the cutoff frequency of 139 GHz and the maximum oscillation frequency of 319 GHz.

G3.8
Width and Gap Dependent Performance of Ferroelectric Coplanar Waveguide Phase Shifter Based on (Ba,Sr)TiO3 Thin Films.
Seung Eon Moon[1], Eun Kyoung Kim[1], Min Hwan Kwak[1], Young Tae Kim[1], Han Cheol Ryu[1], Su Jae Lee[1], Kwang Yong Kang[1] and Won-Jeong Kim[2]; [1]ETRI, Daejeon, South Korea; [2]Changwon National University, Changwon, South Korea.

(001) oriented (Ba,Sr)TiO3 (BST) thin films were deposited on MgO (001) single crystal substrates by the pulsed laser deposition method. Structural properties of BST films were investigated using X-ray diffractometer. Coplanar waveguide (CPW) device based on BST/MgO layer structure was fabricated by dc sputtering deposition, photolithography and etching process. To study the geometrical factor dependent microwave performance of the CPW phase shifter based on (001) oriented (Ba,Sr)TiO3 (BST) film, the CPW devices having various gap and width were fabricated. The microwave dielectric properties of BST CPW phase shifter devices were examined by calculating the scattering parameter obtained using a HP 8510C vector network analyzer with the frequency range $0.5 - 20$ GHz at room temperature under the dc bias field of $0 - 40$ V. The measured reflection loss and insertion loss at 10 GHz with no dc bias were about $-18 - -4$ dB and $-15 - -2$ dB, which mainly depended on the impedances of the CPW transmission lines. The measured differential phase shift values were about $30\,^{\circ} - 120\,^{\circ}$ at 10 GHz with 40 V dc bias variation, which depended on the gap size.

G3.9
Effect of Ta_2O_5 on Dielectric Properties of Forsterite Ceramics.
Dong-Young Kim, Dong-Suk Jun, Hong-Yeol Lee and Sang-Seok Lee; Ultra high speed communication IC Team, Electronics and Telecommunications Research Institute, Daejeon, South Korea.

Frequencies of a millimeter-wave band, which are superhigh frequencies of over 30GHz, are investigated to be used for a next-generation communication service. Demands for low loss dielectrics in millimeter-wave band are increased according to these technical trends to develop the millimeter wave communication system. Especially, in the NRD (Nonradiative dielectric) guide devices, the insertion loss of devices are critically related to the dielctric quality factor. Therefore, development of low loss dielectric is essential for the commercialization of NRD guide devices. For these purpose, forsterite-based ceramics were produced. The dielectric was manufactured by conventional ceramic processing. High purity MgO,

SiO_2, and Ta_2O_5 powders were used as raw materials. These powders were mixed with appropriate ratio by ball milling. The mixed powders were calcined at 1200°C for 4 hours. The calcined powder was sintered at 1350 1650°C for 4 hours. The apparent density of the sintered sample was measured by the Archimedes method. The crystalline phase and microstructure were identified by powder X-ray diffraction (XRD) and scanning electron microscopy, respectively. The dielectric constant was measured in the TE_{011} mode using the Hakki and Coleman method. Pure forsterie (Mg_2SiO_4) shows porous microstructure and very low dielectric quality factor (Q*f), which is not suitable for the dielectrics used in millimeter-wave band. The dielectric constant and Q*f value of pure forsterite ceamics sintered at 1650°C was 5.6 and 38,000 GHz, respectively. The relative density was 2.6 g/cm^3 which is 83% of theoretical density. This means that the sintering temperature of 1650°C was not sufficient for full densification. This insufficient densification deteriorated the dielectric properties of sintered samples, and the sample had low dielectric constant and low dielectric quality factor. Therefore, additive material was needed to reduce the sintering temperature and to enhance the dielectric characteristics of sintered sample. Several materials were attempted as a sintering aid. Among them, Ta_2O_5 was effective additive to enhance the sinterability and dielectric characteristics. The addition of Ta_2O_5 increased dielectric constant over 7.4, and Q*f value over 150,000 GHz, but decreased the sintering temperature by about 250°C. In this presentation, the effect of Ta_2O_5 on the sintering characteristics and dielectric properties of forsterite will be presented.

G3.10

MIM Capacitor Using ALD Al2O3 for RF IC and DRAM applications. Sung Yong Ko[1], Jung Ik Oh[1], Cheol Yeong Jang[1], Young Ho Bae[2], Young Chul Jung[3] and Yong Hyun Lee[1]; [1]Dept. of Electronics, Kyungpook National University, Daegu, South Korea; [2]Division of Information and Communication Engineering, Uiduk University, Gyungju, Gyongbuk, South Korea; [3]School of Computer and Electronics, Gyungju University, Gyungju, Gyongbuk, South Korea.

In this paper, Al2O3 thin film which has a relatively high dielectric constant was deposited by atomic layer deposition(ALD) using Methyl-Pyrrolidine-Tri-Methyl-Aluminum(MPTMA) and H2O on Ti. And metal-insulator-metal(MIM) capacitors were fabricated in a coplanar waveguide type and measured. Deposition temperature of Al2O3 thin film was 200 °C. Its thickness was 300 Å. As a result, capacitance density of fabricated MIM capacitor was 0.229 μF/cm2 and it had lower voltage coefficients of capacitance(VCC) and leakage currents than Al2O3 MIM capacitor prepared by Al oxidation[1] and Si3N4 MIM capacitor prepared by PECVD[2] respectively. The RF measurement with network analyzer shows that Al2O3 MIM capacitor prepared by ALD wasn't resonant below 10.2 GHz. The capacitance of MIM capacitor that was 1.6 pF at 1 MHz was 1.41 pF at 1 Ghz. It had 10 % differences of capacitance until 5.6 GHz. This shows that it has ability to adapt in RF applications. Capacitance characteristics on temperature were analyzed from 30 to 150 °C. Temperature coefficient of capacitance(TCC) of prepared MIM capacitor was 234 ppm/°C at 1 MHz and was 272 ppm/°C at 100 kHz. In this research, it was possible to fabricate Al2O3 MIM capacitor prepared by ALD having low process temperature and exact thickness control. The Al2O3 MIM capacitor prepared by ALD exhibits low voltage coefficient of capacitance(VCC), low leakage current, small frequency-dependent capacitance reduction, low temperature coefficient of capacitance(TCC) and good reliability that is suitable for RF ICs and DRAM. Index Term: High-k, MIM capacitor, Atomic Layer Deposition, Al2O3 Reference [1] S. B. Chen, C. H. Lai, Albert Chin, J.C. Hsieh and J. Liu, "High-Density MIM Capacitors Using Al2O3 and AlTiOx Dielectrics," IEEE Electron Device Lett., Vol. 23, No. 4, pp. 185-187, 2002 [2] Jeffrey A. Babcock, Scott G. Balster, Angelo Pinto, Christoph Dirnecker, Philipp Steinmann, Reiner Jumpertz and Badih El-Kareh, "Anolog Characteristics of Metal-Insulator-Metal Capacitors Using PECVD Nitride Dielectrics," IEEE Electron Device Letters, Vol. 22, No. 5, pp. 230-232, 2001

G3.11

A Study on Thin Film Microstructure and Its Effects on Acoustic Film Velocity Through Picosecond Ultrasonics Technique. Li Ta-Ching[1], Nen-Wen Pu[1], Ben-Je Lwo[1], Jung-Chang Hu[2] and Chin-Hsing Kao[1]; [1]National Defense University , Chung Cheng Institute of Technology, Taoyuan, Taiwan; [2]Chung-Shan Institute of Science and Technogy., Taoyuan, Taiwan.

Longitudinal thin film acoustic velocity is the most important parameter for Solidly Mounted Resonator (SMR) design on wireless communication. To this end, this paper analyzes microstructure properties of the thin films with various techniques and studies the longitudinal film velocity due to microstructure effects. In this work, zirconium oxide films, which were deposited by RF magnetron reactive sputtering with various processing parameters such as oxygen partial pressure and RF power, were first made. We next used the picosecond ultrasonic technique to measure the longitudinal velocity of the thin films. To find the relationship between film velocities and the microstructure, the thin film characters were also evaluated through Fourier transform infrared spectrum (FTIR) for porous; X-Ray diffraction spectrum (XRD) for grain size and phase; and X-Ray photoelectron spectroscopy (XPS) for composition ratio. According to the literature, the longitudinal velocity of bulk zirconia material can be calculated from Young's modulus and the density. However, thin film velocities we measured so far were less than the bulk. To derive more accurate and reliable conclusions, more specimens will be studies and the results will be contained in this paper. With measurement results, processing conditions on thin film deposition will be better controlled, and the actual thin film velocity will be more accurately obtained for SMR designer

G3.12

Microwave Dielectric Properties of Oriented $BaLa_4Ti_4O_{15}$ Ceramics Fabricated by Templated Grain Growth. Yuko Fukami, Kensuke Wada, Ken-ichi Kakimoto and Hitoshi Ohsato; Nagoya Institute of Technology, Nagoya, Japan.

$BaLa_4Ti_4O_{15}$ (BLT) ceramics have excellent microwave dielectric properties with high dielectric constant ϵ_r=45 and high quality factor $Q{\cdot}f$=42,000GHz. However the temperature dependence of resonant frequency (τ_f) is −27ppm/°C. For the resonator applications, it is strongly required to be τ_f of near 0ppm/°C. Usually, τ_f was improved by changing composition such as formation of solid solution or additive with opposite τ_f for the compensation. In most cases, it can cause severe degradation to ϵ_r and $Q{\cdot}f$ even though τ_f is improved. Consequently, another method is required to improve τ_f without decrease of ϵ_r and $Q{\cdot}f$. BLT has a layer perovskite-type structure and its crystals tend to grow plate-like in shape, because they have a trigonal crystal system and their lattice parameters are a=5.572Å and c=22.48Å. Therefore, it can be candidate material for Templated Grain Growth (TGG) method. We confirmed that BLT crystals sintered with BLT powder showed the $(00{\cdot}l)$ orientation and grain growth. In this study, we fabricated unique microstructure by TGG method. Single phase, plate-like BLT template particles were prepared via a molten salt synthesis using NaCl, KCl and NaCl-KCl flux. BLT ceramics with an unique texture were obtained by TGG method using a doctor-blade technique. Plate-like BLT template particles were mixed with powders synthesized by solid-state reaction, and unidirectionally aligned by casting. During sintering, oriented BLT grains acted as seeds for the anisotoropic grain growth within the specimens. X-ray diffraction measurements and scanning electron microscope observations revealed that the plate-like BLT grains aligned parallel to the casting direction. The orientation degree of sintered specimen was calculated by Lotgering's method and sintering density was measured. The relationship between anisotoropic microstructure and microwave dielectric properties was also discussed.

G3.13

A Novel Copper Damascene Technique for Power Loaded SAW Structures. Siegfried Bernhard Menzel[1], Matthias Albert[2], Daniel Reitz[1], Hagen Schmidt[1], Manfred Weihnacht[1], Klaus Wetzig[1] and Johann Wolfgang Bartha[2]; [1]Leibniz Institute for Solid State and Materials Research (IFW) Dresden, Dresden, Germany; [2]Electrical Engineering and Information Technology, Dresden University of Technology, Dresden, Germany.

High power applications of Surface Acoustic Wave (SAW) devices may result in microstructural damage of Al-based finger electrodes due to material transport (acoustomigration). The mechanism of acoustomigration is strongly associated with the SAW stress and the temperature of the electrodes material. Therefore Cu thin films exhibit generally a higher performance with respect to operation at higher frequencies, rf input power and higher temperature. However, the use of copper thin films for SAW structures requires capable barrier layers to suppress interactions with the piezosubstrate material and ambience. As demonstrated in earlier work, Ta-Si-N/Cu-film systems are optimally qualified for high power SAW applications [1-3]. In comparison with Al/Ti-layers which are typically applied for SAW devices, the Cu system has a significantly higher SAW power durability and thus a higher reliability and lifetime. Furthermore, using Cu metallizations the SAW technology is generally compatible to microelectronics where electroplated Cu films have replaced Al-alloys. Here we present the application of a Cu damascene technique to SAW structures realizing inlaid Cu electrodes in quartz or LiNbO3-substrates. In comparison to electrodes bearing on substrates such an inlaid Cu structure enables some novel SAW features. With regard to acoustomigration the Cu damascene SAW structure is expected to have lower danger of fatal failures caused by shorts between adjacent fingers. For our study a special power SAW test structure was used which was described elsewhere [3]. But for the Cu damascene technique the inverse (negative) resist mask of the power SAW test structure was realized. The structuring of the fingers trenches into the piezosubstrate was carried out by reactive ion etching technique using a Cu hard mask (lift-off preparation technique). Etched trenches were filled with a Ta-Si-N / Cu-bilayer system by magnetron sputter deposition in a cluster tool, and structured by a chemical-mechanical polishing (CMP) process. Subsequently, after cleaning a thin barrier layer was deposited on the wafers surface which enables sufficient bonding properties of Al-wires. First results of electric measurement show that travelling SAW could be excited in good quality. References [1] Patent DE 102 16 559 A1 [2] S. Menzel, H. Schmidt, M. Weihnacht, K. Wetzig, in Proceed. 6th Internat. Workshop on Stress Induced Phenomena in Metallizations, Ithaca, AIP 612, Melville (2002), p. 133 [3] S. Menzel and K. Wetzig, in K. Wetzig and C.M. Schneider (Eds.): Metal Based Thin Films for Electronics. Whiley-VCH, Weinheim (2003), p. 235

G3.14
Modelling Leakage Current in (Ba,Sr)TiO_3 Films.
Sanjib Saha[1], Stephen K. Streiffer[1] and David Y. Kaufman[2]; [1]Materials Science Division, Argonne National Laboratory, Argonne, Illinois; [2]Energy Technology Division, Argonne National Laboratory, Argonne, Illinois.

High dielectric constant thin films of perovskite oxides such as barium strontium titanate (BST) have captured the attention of researchers for more than a decade now. The fuel for such research has been the increasing demand from industry for better-performing dielectrics, to replace traditional ones. While such materials are already being integrated into various devices, a complete understanding of electronic properties is still lacking. A crucial part of this understanding centers on the leakage behaviour of these BST films. Previously several authors have modelled the leakage current of BST thin films based on Richardson-Schottky and Fowler-Nordheim mechanisms. These models have generally been in good agreement with experimental observations of the leakage currents. Following in particular the Baniecki [1] approach, we have modelled the variation of potential, electric field and local permittivity in Pt/BST/Pt heterostructures, also incorporating field-dependent dielectric behavior as described by phenomenological Landau-Ginzburg-Devonshire theory. This gives a working model that can quantitatively estimate the local permittivity of the film as a function of its thickness and with variations in temperature and applied electric field. Corrections arising from extrinsic interfacial effects such as the surface-dead-layer model and the Thomas-Fermi screening effect for metallic electrodes have also been incorporated into our simulations. The above calculations were used to determine the leakage characteristics of BST thin films using basic Richardson-Schottky equations. This model is able to reproduce to the experimentally- observed positive temperature-coefficient of resistance (PTCR) behaviour found in BST films. The impact of changing the thickness of the BST film and the thickness effect on the PTCR behaviour will be highlighted. Comparison of these results with experimental observations will be shown for films grown using MOCVD. [1] J. D. Baniecki et al. J. Appl. Phys. 89, 2873 (2001)

G3.15
Abstract Withdrawn

G3.16
Middle-permittivity LTCC dielectric compositions with adjustable temperature coefficient. Jae-Hwan Park, Young-Jin Choi, Jeong-Hyun Park and Jae-Gwan Park; Multifunctional Ceramics, Korea Institute of Science and Technology, Seoul, South Korea.

Middle-permittivity LTCC dielectric compositions with adjustable temperature coefficient have been studied based on CaZrO3-CaTiO3. To lower the densification temperature from 1450oC to less than 900oC, a series of lithium-borosilicate glass system was designed and added to CaZrO3-CaTiO3 system. As the tcf of glass frits and CaZrO3 are slightly negative (-5 - 200ppm/oC) and that of CaTiO3 is significantly positive, zero tcf could be realized by mixing an appropriate amount of CaTiO3 (10 - 20wt%) with CaZrO3. Microstructures, physical properties, and microwave dielectric properties were measured as a function of the compositional ratio of CaZrO3-CaTiO3. Nearly zero tcf together with acceptable microwave quality factor were obtained at the composition of CaZrO3:CaTiO3:frit=70:15:15wt%.

G3.17
Characteristics of Copper Film on the Polymer Substrate Deposited by a Cyclic Operation of and Magnetron Sputtering Coupled with ECR-MOCVD. Joong-Kee Lee[1], Bup-Ju Jeon[1], Sang Duk Myung[2] and Dongjin Byun[2]; [1]Eco-Nano Research Center, KIST, Seoul, South Korea; [2]Department of Material Science & Engineering, Korea University, Seoul, South Korea.

In order to employ the metallized polymer as a flexible copper clad laminate, enhancement of adhesion between the metallic layer and plastic substrate, and c.a. 4-5 micrometer thickness range of copper film should be required. The conventional methods for the metallization of polymer under low temperature process are physical coating methods such as magnetron sputtering and evaporation. Magnetron sputtering method is convenient to operate and get high deposition rate. However, it has a limitation of thickness of metallic layer caused by poor adhesion. Recently, we found that metallic organic chemical vapor deposition (MOCVD) could be possible at room temperature when a pulse negative voltage is applied to the near of the polymer substrate. The high efficiency in exciting the reactants under ECR plasma coupled with negative voltage from a DC bias allows the deposition of copper films at room temperature with excellent adhesion. We have reported before that metallized polymer with good adhesion could be prepared by ECR-MOCVD method at room temperature with the aid of pulse negative DC bias near the substrate. However, the deposition rate of copper film was very low compared with that of magnetron. In this work, cyclic operation of magnetron sputtering couple with ECR-MOCVD was tried in order to obtain the micro-meter ranged thickness copper films with good adhesion on the polymer substrate. Here, cyclic operation is a mode of running the ECR-MOCVD coupled with a magnetron sputtering system in which magnetron sputtering is periodically operated under continuous operation of MOCVD between two predetermined operating times. The cycled period is the time that elapses between repetitions of the same conditions. Split is the fraction of the cycled periods during which magnetron sputtering operates. In practice, this means that magnetron sputtering is used intermittently to enhance the copper deposition rate under ECR-MOCVD system. In this work, effects of cycled operation modes of magnetron sputtering on characteristics of copper films prepared were investigated.

G3.18
Influence of Non-Stoichiometry on the Ordering in Ba(Ni1/3Ta2/3)O3 Microwave Dielectrics. Niti Yongvanich and Peter K. Davies; Materials Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania.

Complex perovskites with the general formula Ba(B′1/3B″2/3)O3 display very high quality factors (Q) in the microwave region and are widely utilized as frequency filters in wireless communication devices. Previous reports on Ba(Zn1/3Ta2/3)O3 (BZT) and other ″1:2″ perovskites have shown the Q factors are enhanced in ceramics with a high degree of cation order; however, the losses are mediated through the formation of ordering induced domain boundaries. Through investigations conducted on Ba(Ni1/3Ta2/3)O3 (BNT) we have found the size of the ordered domains is strongly dependent upon the size and density of the sintered ceramic pellets; larger pellets show a domain size gradient or coring that deteriorates Q. The coring effect can be eliminated and the Q value improved, by sintering pellets formed from pre-ordered powders. However, even the preordered BNT powders require annealing times of at least 32 hours at 1500 °C to reach a large domain, fully ordered state and they do not sinter to as high a density as their partially ordered counterparts. In an attempt to overcome the slow ordering kinetics of BNT we have examined the effect of small concentrations of B-site vacancies on the phase stability and ordering of BNT powders and ceramic pellets. Structure studies reveal that BNT can accommodate ~3% Ni vacancies on the B-site, with a corresponding concentration of oxygen vacancies. The effect of the vacancy formation on the kinetics of the ordering reactions, domain sizes and microwave dielectric properties will be discussed.

G3.19
The effect of annealing for dielectric properties of Ti doped K(Ta,Nb)O_3 thin film using PLD. Hyung-jin Bae[1], Jennifer Sigman[1], L. A. Boatner[2] and David P. Norton[1]; [1]Mat. Sci. & Eng., University of Florida, Gainesville, Florida; [2]Condensed Matter Science Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

K(Ta,Nb)O_3 (KTN) has been widely studied for optical wave guides and tunable microwave applications due to its non-linear properties. For tunable microwave applications, high tunability, and low dielectric loss under small operable bias are required. In this study, epitaxial $KTa_{0.524}Nb_{0.446}Ti_{0.03}O_3$ films with 3% Ti were investigated. Titanium (+4) substitution on the Nb/Ta site should reduce dielectric losses of KTN:Ti film by introducing an acceptor state. This acceptor state traps electrons due to oxygen vacancies that form during oxide film growth. KTN:Ti films were grown using pulsed laser deposition, and then annealed at different temperatures in oxygen ambient. The crystallinity, and surface morphology of KTN:Ti film were investigated using x-ray diffraction, and atomic force microscopy. The dielectric properties of Ti doped KTN films measured for unannealed and annealed films will be reported. Tunability and dielectric loss of as-deposited KTN:Ti film were determined to be 10% and 0.0134, respectively. For films annealed at 800°C and 900°C, the dielectric loss decreased but with a decrease in tunability as well.

G3.20
Abstract Withdrawn

G3.21
Integrated On-chip Solenoid Inductors with Patterned Permalloy Cores for High Frequency Applications.
Jinsook Kim[1] and Edwin C. Kan[2]; [1]Cornell University, Ithaca, New York; [2]Cornell University, Ithaca, New York.

Jinsook Kim, Edwin C. Kan, School of Electrical and Computer Engineering, Cornell University, Ithaca, NY. The on-chip passive inductors for high frequency applications are a key microwave integrated circuit element, where air-core spiral inductors have been a common practice because inductors with ferromagnetic core has been considered as relatively poor at high frequency [1]. Considering capacitive loss, Eddy current loss, resistive loss, and easy/hard axis orientation in ferromagnetic resonance, we have designed and characterized solenoid inductors with various permalloy core patterns, including pie, vertical bars, multi-ring, and cylinders with air core as the control sample. The influence from permalloy core patterns on the Q-factor and inductance between 500MHz and 10GHz is investigated. Multiple solenoids in serious and parallel are used to distinguish the importance of capacitive and resistive losses, while the external magnetic field is applied to investigate the range for ferromagnetic resonance effects. For each solenoid structure in the design phase, the analytical calculation and EM field simulation by HFSS (High-Frequency Structure Simulator) are performed to estimate the magnetic field flux density as a function of distance from the solenoids inductors. The fabrication starts from a high-resistance Si substrate with 15,000 Wcm to reduce the substrate loss. A PECVD oxide of 5mm is deposited before the lift-off signal line and permalloy structures. Gold of 0.4mm with Ti adhesion layer of 20nm is evaporated for the signal lines of the solenoids inductors. Various patterned permalloy cores with Ti adhesion layers are also evaporated, patterned by individual lift-off process. The permalloy layer has the same thickness as the Au layer, so is the adhesion layer. With the S-parameter measurements from the fabricated solenoid inductors, the open-short-through de-embedding procedure [2] and parameter extractions [3] can be done with rigorous equivalent circuit models to obtain Q-factor, inductance and resistance as a function of frequency. We have found inductance and Q factor improvement up to 15GHz operations for patterned permalloy structures. The permalloy pattern design also affects the extracted values due to effects from fill ratios and Eddy current loss. References: 1. J. Y. Park, and M. G. Allen, IEEE Trans. on Advanced Packaging vol. 22, May 1999, pp207-213. 2. C. Chen, and M. J. Deen, Trans. on Microwave Theory and Techniques, vol. 49, No.5, May 2001, pp.1004-1005. 3. R. L. Bunch, D.I. Sanderson, and S. Raman, IEEE Microwave Magazine, 2003, June, 2002, pp. 82-90. Jinsook Kim, Cornell University, School of Electrical and Computer Engineering, 323 Phillips Hall, Ithaca, NY, 14853, USA, Tel: 607-254-8842, FAX: 607-254-3508, jk368@cornell.edu

G3.22
Tuning THz Wave by Ferroelectric Thin Films. Kenta Kotani, Mukul Misra, Iwao Kawayama, Hironaru Murakami and Masayoshi Tonouchi; Research Center for Superconductor Photonics, Osaka University, Suita, Osaka, Japan.

Ferroelectric thin films of $SrTiO_3$ (STO), $BaTiO_3$ (BTO) and $Ba_xSr_{1-x}TiO_3$ (BSTO) have been extensively explored for their application to tunable microwave devices and high-density dynamic random access memories. These thin films can also be utilizes for similar applications in THz frequency domain. The rapid developments in the generation and detection techniques of THz waves during last decade made it feasible to apply this frequency domain for various kinds of applications and therefore it requires a variety of devices such as reliable frequency tunable, phase and time delay components at this frequency range. The high quality epitaxial BTO, STO and BSTO thin films were grown on the MgO substrates by pulsed laser deposition. We have studied their properties in the frequency range from 100 GHz to 1.5 THz in the temperature range from 20 K to 290 K by THz time domain spectroscopy method. After the measurement of THz time domain spectroscopy, the interdigital electrodes of Ti and Pt were sputtered fabricated by standard photo lift-off technique on these thin films to measure their dielectric properties at sub MHz and MHZ frequencies. The real and imaginary parts of the dielectric constant of the thin film have been measured from room temperature to 20 K in the cooling process. The STO and BSTO thin films show their characteristic phase transitions at respective temperatures. The loss tangent of these thin films at room temperature is of the order of 10-2 indicating a high quality of thin films. Moreover among these thin films, the BSTO thin film show the maximum change in the value of dielectric constant with the applied voltage bias at room temperature, therefore we choose BSTO thin film for tuning the THz wave at room temperature by applying voltage bias to the interdigital electrodes fabricated on the BSTO thin film. The tuning of THz waveforms by BSTO thin film has been studied by pump-probe THz time domain spectroscopy (THz-TDS) setup in the frequency range from 0.3-1.2 THz. Laser pulses from a mode locked Ti:sapphire laser of pulse width 100 fs and repetition rate 82 MHz was used to trigger/gate dipole type LT-GaAs photoconductive switch emitter/detector. The thin film sample was mounted on a fixed sample holder. THz waveforms after transmission through thin film before and after applying voltage bias to interdigital electrodes have been measured in time domain at room temperature. The samples were adjusted to the position so that THz wave could pass through the area which is covered with the interdigital electrodes. We have observed a slight change in time delay and amplitude of the transmitted THz wave form. The intensity of the peak of the waveform increases with a slight forward change in the phase by applying the bias voltage. Our experiment result demonstrates that these thin films can be used for future frequency agile THz devices.

G3.23
Compositions from the BST and PZT Solid Solution Families Deposited on Low Cost Substrates. Jon-Paul Maria, Department of MS&E, North Carolina State University, Raleigh, North Carolina.

The integration of high permittivity dielectric materials in high volume application has been a long sought after goal pursued by numerous researchers since the mid 1980's. Appreciation of this goal has been slower than anticipated for a variety of reasons, perhaps most importantly, the incredible complexity of ferroelectric materials under challenging physical, electrical, and mechanical boundary conditions. An additional reason for the slow rate of progression has been associated with the high cost of integration imparted by an expensive complement of electrode materials and the complicated process flows for deposition and patterning. In this presentation we discuss recent efforts at NCSU to develop methods for preparing device quality ferroelectric thin film processes that overcome several cost and complexity issues. We will focus on compositions from the BST and PZT solid solution families deposited on low cost substrates like base metal foils. These foil-based devices are targeted towards embedded capacitors, however, numerous high volume applications can be envisaged. The materials challenges associated with this work are centered upon achieving process compatibility as it pertains to thermal expansion, chemical reactivity, and interface formation. In all cases, the necessary pathways to success involve careful maintenance of the process flows. Our processes for chemical solution deposition of BT on Cu will be discussed, with specific attention to the achievement of permittivity values in excess of 3000 in film thicknesses less than 0.6 μm. Similarly we will demonstrate low loss tunable dielectrics can be prepared on copper by sputtering, with dielectric quality factors in excess of 300 in the absence of any chemical barrier layers. Finally, we will show recent results for tunable microwave filters prepared on these low embodiments.

SESSION G4: Passives
Chairs: Don Shiffler and Harrie A. C. Tilmans
Tuesday Morning, November 30, 2004
Liberty (Sheraton)

8:30 AM *G4.1
Embedding Ceramic Thick-Film Capacitors into Printed Wiring Boards. William Borland, Marc Doyle, Lynne Dellis, Olga Renovales and Diptarka Majumdar; DuPont Electronics, Research Triangle Park, North Carolina.

Embedding passives into printed wiring boards have numerous advantages that show up in different segments of the market. For example, the ability to locate decoupling capacitors within a couple hundred microns of semiconductor I/Os greatly improves response time and signal integrity leading to product performance improvements. One crucial need, however, is high capacitance density. High capacitance density can only be readily achieved by ceramic technology. Therefore, the focus of this work has been the development of ceramic thick-film capacitor technology that can be used to bury high capacitance density components within an organic substrate. This allows high value decoupling capacitors to be buried for chip packaging or related applications in spaces available within any layer of the substrate. The dielectric paste is based on doped barium titanate composition and works together with a cofired copper electrode paste. The capacitor system is designed to be screen printed on copper foil in the locations desired in the circuit and fired in nitrogen at 900 ^oC degree to form the ceramic components. Following this, the foil is laminated, component face down, to the organic laminate using standard prepreg and the inner layer etched to reveal the components in an organic matrix. The system has a dielectric constant of approximately 4000 and achieves a capacitance density of 1.5 nF/mm2. In the following sections, some process issues are discussed and test data for electrical performance and reliability are presented.

9:00 AM *G4.2
Dielectric Thin Films for Integrated Passive Components.
Susan Trolier-McKinstry, Jian-Gong Cheng, Mustafa Burak Telli and Hajime Nagata; Materials Science and Engineering, Penn State, University Park, Pennsylvania.

In the development of thin film integrated passive components, a combination of low processing temperatures, and the ability to prepare a range of compositions spanning different permittivities and temperature dependences is desirable. This paper reviews recent approaches to achieving these ends. While it is difficult to achieve low processing temperatures in all cases, it has been found that chemical solution deposited bismuth zinc niobate can be crystallized below 400C by pulsed laser annealing. The resulting films on Pt-coated Si substrates have dielectric constants of 178, loss tangents below 1%. and temperature coefficients of capacitance of -285ppm/C. Deposition on Ni-coated kapton substrates has also been demonstrated. For intermediate permittivities, the silver tantalate niobate (ATN) system provides permittivities from 50 - 400, coupled with reasonable Q's in the microwave for some compositions. A chemical solution deposition route was developed for ATN. It is difficult to prepare single phase perovskite films on Pt-coated substrates, but epitaxial perovskite films were achieved on SrRuO3/LaAlO3, with permittivities comparable to those of bulk materials. Finally, the development of high permittivity, lead-free, dielectric films will be discussed.

9:30 AM G4.3
Scaling Effects in PLZT/Ni Film-on-Foil Capacitors For Embedded and Discreet Capacitors.
David Y. Kaufman[1], Sanjib Saha[2] and Stephen K. Streiffer[2]; [1]Energy Technology Division, Argonne National Laboratory, Argonne, Illinois; [2]Materials Science Division, Argonne national Laboratory, Argonne, Illinois.

PLZT thin films on metal foils are promising elements for high-K embedded passives and high volumetric efficiency discreet devices. The effects of increasing PLZT thickness on the dielectric and electrical properties were examined with the intent of sustaining higher voltages in film-on-foil capacitors. A thickness series of PLZT thin films from 0.7 to 2.5 microns were deposited on Ni foils by chemical solution deposition (CSD). Increasing the PLZT thickness increased the apparent dielectric constant due to diminishing influences of a parasitic capacitance at the PLZT/Ni interface. Microstructural aspects of the interfacial reactions will be shown. To remove the influence of interfacial effects a $LaNiO_3$ buffer layer was inserted between the PLZT and Ni foil. Capacitance densities as high as 1.5 microfarads per square centimeter could then be achieved. The high materials uniformity and density afforded by CSD enabled breakdown fields as high as 1.8 MV/cm to be maintained even in relatively thick films (440 V across a 2.4 micron PLZT film). The leakage current behavior and temperature response of the dielectric properties as a function of PLZT thickness, with and without a $LaNiO_3$ buffer layer, will be presented. Application of this technology in both embedded passives and discreet devices will be highlighted.

9:45 AM G4.4
Abstract Withdrawn

10:30 AM *G4.5
Materials Issues in Epitaxial Ferrite Thin Films for Microelectronic Applications.
Yuri Suzuki[1], Yayoi Takamura[1], Rajesh V. Chopdekar[1], Darren Dale[2] and Guohan Hu[3]; [1]Materials Science and Engineering, UC Berkeley, Berkeley, California; [2]Materials Science and Engineeering, Cornell University, Ithaca, New York; [3]Hitachi Global Storage Technologies, San Jose, California.

Ferrites constitute a class of materials that has been recognized to have significant potential in applications ranging from millimeter wave integrated circuitry to magnetic recording. In particular, epitaxial ferrite films have provided not only technological promise for the incorporation of magnetically tailored thin film materials in a variety of applications but also an understanding of the structure-property relationships in this family of materials. From a more fundamental perspective, epitaxial ferrite films have provided a model system in which, for example, the effects of perpendicular exchange coupling, modified superexchange interactions and nearly ideal exchange coupling have been observed. In this talk, we will focus on examples displaying these phenomena and functionality in epitaxial ferrite thin films through our studies of nearly ideal exchange coupling in spinel structure ferrite heterostructures, structural tuning of ferrite films via strain and cation distribution, and magnetically tailored spinel and garnet structure ferrite heterostructures.

11:00 AM *G4.6
Ferrite Properties and Technology Issues for Improved Microwave Systems.
Gerald F. Dionne, MIT Lincoln Laboratory, Lexington, Massachusetts.

Microwave device engineers continually seek materials advances to improve performance of magnetic components at reduced size and cost. Wherever possible, microstrip or stripline device configurations are adopted in preference to bulky waveguide structures. For the past decade, the goals have also included the deposition of thick-film ferrites of spinel, garnet, or hexagonal crystal structures for monolithic integration with semiconductors, such as Si and GaAs [1]. More recently the prospects of using more-refractory SiC have attracted increased attention and a renewal of interest in previous work. In radar and communications applications, the nonreciprocal propagation properties of ferrites are essential in systems requiring the action of phase shifters, circulators, and isolators [1]. The introduction of superconductor circuits has led to the development of very low-loss phase shifters and circulators [2]. Recent demonstrations of rf permeability tuning by controlling the state of magnetization at very low magnetic fields has led to the development of high-speed, high-Q tunable filters [3]. In this paper, design issues of four classes of microwave device are reviewed: (1) self-biased microstrip circulators with normal or in-plane magnetic bias, (2) microstrip tunable filters, (3) low-loss microstrip phase shifters, and (4) high-power quasi-optical millimeter-wave circulators that include self-bias options. [1] J.D. Adam, L.E. Davis, G.F. Dionne, E.F. Schloemann, and S.N. Stitzer, IEEE Trans. Microwave Theory Tech. 50, 721 (2002). [2] G.F. Dionne, D.E. Oates, D.H. Temme, and J.A. Weiss, IEEE Trans. Microwave Theory Tech. 44, 1361 (1996). [3] D.E. Oates and G.F. Dionne, IEEE Trans. Appl. Supercond. 9, 4170 (1999).

11:30 AM G4.7
Regular composites based on thin iron films for microwave applications.
Ilya A. Ryzhikov, Igor T. Iakubov, Andrey N. Lagarkov, Sergey A. Maklakov, Aleksey V. Osipov, Konstantin N. Rozanov and Sergey N. Starastenko; Institute for Theoretical and Applied Electromagnetics of RAS, Moscow, Russian Federation.

Materials with high microwave permeability are of practical importance for many applications, such as magnetic sensors, tunable microwave filters, magneto-dipole antennas, etc. These materials are typically composites filled with ferromagnetic metal or alloy inclusions. The usage of composites instead of bulk materials allows to diminish conductivity losses and to improve the microwave performance. The largest value of the microwave permeability can be achieved with planar situated flat particles with in-plane magnetic anisotropy and can be evaluated by Acher's formula [1]: $(\mu\text{s-}1)\text{fres}\hat{2}=(\gamma 4\pi \text{Ms})\hat{2}$, with the static permeability μs, the resonance frequency fres, and the saturation magnetization Ms of the ferromagnet, and γ =2.8 GHz/kOe. The presentation reports a technology development and investigation of microwave properties of composites filled with planar magnetic particles. The samples under study are regular composite structures comprising circular spots of iron films of sub-millimetre diameter. The samples are fabricated by chemical etching of multilayer metal-dielectric laminates produced on flexible polymer substrate by the RF magnetron sputtering. The developed technology permits us to produce the films with desirable frequency dependence of magnetic permeability. The permeability is measured in a coaxial measuring cell in the frequency range of 0.1 to 10 GHz [2]. The measurements were also conducted with the permanent external magnetic of up to 500 Oe. The results are discussed in terms of effective magnetic properties of the manufactured composites. The influence of the parameters of preparation process on the measured frequency dependences of effective permeability is studied and analyzed. It is shown that composites of multilayer patterned magnetic films enable one to obtain dispersion dependences of magnetic permeability of the desirable form and alter the shape, width and position of resonance.

11:45 AM G4.8
Optimization of Passive Isolator Based On Barium Ferrite Sputtered Films.
Martine Le Berre[1], Stephane Capraro[2], Jean -Pierre Chatelon[2], Thomas Rouiller[2], Bernard Bayard[2], Daniel Barbier[1] and Jean-Jacques Rousseau[2]; [1]LPM, INSA Lyon, Villeurbanne, France; [2]DIOM, Universite JeanMonnet, Saint-Etienne, France.

Ferrites have magnetic properties suitable for electronic applications, especially in the microwave range (circulators and isolators). Hexagonal ferrite, such as barium ferrite (BaFe12O19 or BaM), which have a large resistivity and high permeability at high frequencies are of great interest for microwave device applications. This contribution deals with BaM films, 1 to 30 microns thick, which were deposited under optimized conditions by RF magnetron sputtering. The films were then crystallized using a 800 C thermal annealing under air. Isolators were then realized using patterning of coplanar wave guides with standard lift-off technique. The slots and the central width were set to 300 mkm, gold was used for the lines. We evaluated the influence of various parameters on the device performances: the magnetic film thickness, the positioning of the magnetic film (whether buried in the CPW or under the CPW), the CPW metallic thickness

and the substrate. As standard design, the CPW were deposited on the top of the magnetic film. For this design, transmission coefficients showed a non reciprocal effect, which reaches 5 dB per cm of line length at 50 GHz for a 26 mkm thick BaM film. Both the insertion losses and the non-reciprocal effect measured increased with the magnetic film thickness. When the magnetic film is buried in the CPW, the isolation effect is increased and insertion losses decrease in comparison to the standard design. Moreover, in this case the isolation effect increased with the conductor thickness as the interaction between the magnetic film and the metal increases.

SESSION G5: Tunable/High k Thin Films II
Chairs: William Nothwang and Don Shiffler
Tuesday Afternoon, November 30, 2004
Liberty (Sheraton)

1:30 PM *G5.1
Recent Advances in Microwave Applications of Thin Ferroelectric Films at the NASA Glenn Research Center. Robert R. Romanofsky[1], Fred W. Van Keuls[2] and Matthew D. Valerio[1]; [1]Antenna, Microwave and Optical Systems Branch, NASA Glenn Research Center, Cleveland, Ohio; [2]Ohio Aerospace Institute, Brookpark, Ohio.

We report on recent developments in microwave applications and understanding of thin BaSrTiO3 films. Most of our recent efforts have focused on developing low loss, wide band phase shifters from X-band (8.4 GHz) to Ka-Band (26.5 GHz) for scanning reflectarray antennas. We have demonstrated a hybrid device at X-band that produces in excess of 300 degrees of phase shift with less than 3 dB insertion loss and greater that 10% bandwidth. Novel planar transmission line designs and results at Ka-band will be presented. The effects of mild (600 rad Si) proton radiation on device performance will be discussed. Preliminary results on optical phase shifters will be included. Prospects for mm-wave devices to 110 GHz, in the context of loss tangent and tuning, will be presented based on experimental measurements.

2:00 PM G5.2
Stroboscopic X-Ray Diffraction Measurements of a Sub-ns Domain Dynamics in Ferroelectric Films. Emil Zolotoyabko[1], John Quintana[2], David J. Towner[3] and Bruce Wessels[3]; [1]Materials Engineering, Technion, Haifa, Israel; [2]DND-CAT Synchrotron Research Center, Northwestern University, Argonne, Illinois; [3]Materials Science and Engineering, Northwestern University, Evanston, Illinois.

Ferroelectric thin films have promising applications for random access memories and electro-optic devices. Domain dynamics is the major factor, which determines the speed of device operation. In this study, the pulsed synchrotron radiation from the Advanced Photon Source at Argonne National Laboratory was used to stroboscopically measure the structural response of ferroelectric films subjected to a high-frequency electric field, which was strong enough to stimulate domain movements. For this purpose, electric pulses with frequency 6.517 MHz from a synchrotron bunch clock generator were passed through a programmable delay unit (the minimal step was 18 ps) and delivered to the input of a frequency synthesizer. The latter generated a sinusoidal-signal of multiple frequencies, which was synchronized (phase-locked) with the x-ray bursts coming to the sample position and, after amplification, applied to the ferroelectric film. We show that stroboscopic measurements of lattice parameters at different delay times make domain dynamics visible and allow us to obtain spectral characteristics of domain motions [1,2]. Samples in this study were 200 nm thick BaTiO3 films epitaxially grown by metal-organic chemical vapor deposition on a 500-micron thick (100)MgO substrates. An external electric field was applied through gold interdigital electrodes with a 5-micron spacing between fingers deposited on top of the films. This design allowed us to drastically reduce the sample capacitance and, correspondingly, the time constant of electrical circuit [1]. We measured the shapes of the (200)BaTiO3 diffraction profiles in the Laue (transmission) scattering geometry, as a function of the delay time, in order to follow modifications of the in-plane lattice parameter parallel to the applied electric field. The time dependences of lattice parameter measured in the frequency range between 25 MHz and 1.3 GHz demonstrated both periodicity and attenuation features related to domain dynamics. Two order of magnitude reduction of the attenuation time (i.e. remarkable increase in damping) was found with increasing electric field frequency. We succeeded to measure attenuation times down to 400 ps. Experimental findings are analyzed in terms of hindering the domain wall motion by generated deformation waves. We found that at frequencies higher than 500-600 MHz, the domain motions in BaTiO3 films become over-damped, information that may be important to future device operation. [1] E. Zolotoyabko, J. P. Quintana, B. H. Hoerman, and B.W. Wessels. Appl. Phys. Lett., v. 80, 3159-3161 (2002). [2] E. Zolotoyabko, J. P. Quintana, D. J. Towner, B. H. Hoerman, and B. W. Wessels. Ferroelectrics, v. 290, 115-124 (2003).

2:15 PM G5.3
Dielectric and Optical Properties of Perovskite-Type Artificial Superlattices. Takakiyo Harigai[1], Song-Min Nam[1], Hirofumi Kakemoto[1], Satoshi Wada[1], Keisuke Saito[2] and Takaaki Tsurumi[1]; [1]Tokyo Institute of Technology, Tokyo, Japan; [2]BRUKER AXS K. K., Yokohama, Japan.

$BaTiO_3/SrTiO_3$ artificial superlattices with the perovskite-type structure exhibit some interesting experimental results, although physical properties of the artificial superlattices have not been clearly understood yet. To elucidate the origin of some unique properties observed in the superlattices, it is required to study the relationship between the structure and the material properties using various type artificial superlattices. In this study, we fabricated $BaTiO_3/SrTiO_3$, $BaTiO_3/BaZrO_3$, and $SrZrO_3/SrTiO_3$ artificial superlattices on $SrTiO_3$ substrates by the molecular beam epitaxy process. The stacking periodicity was varied from 1 unit cell to 40 unit cells, and the total thickness was fixed at 80 unit cells of the primitive perovskite lattice. Structures of the superlattices were analyzed by reflection high-energy electron diffraction, normal θ-2θ scan mode x-ray diffraction, and the reciprocal space mapping measurement. The refractive indexes of the superlattice were measured by a rotating-analyzer type spectroscopic ellipsometer in the wavelength range of 350-850 nm. The capacitance and the complex admittance of the superlattices with interdigital electrodes were measured using an impedance analyzer at frequencies from 1 kHz to 110 MHz, and charge vs. voltage (Q-V) hysteresis curves were measured. It was clarified that the dielectric permittivity and the refractive index changed by the superlattice periodicity and those of 10-periodic superlattice was lager than those of other specimens. In the case of the $SrZrO_3/SrTiO_3$ system, a clear hysteresis curve was observed on 10-periodic superlattice, suggesting that the ferroelectricity was induced into the superlattices although both of $SrZrO_3$ and $SrTiO_3$ showed paraelectricity in nature. It seemed that the anisotropic lattice distortion induced by the lattice mismatch was the origin of the physical properties.

3:00 PM G5.4
Metal Oxide Electrode in Ferroelectric Capacitors For Microwave Applications. Sriraj Manavalan[1], Ashok Kumar[2] and Thomas Weller[1]; [1]Electrical Engineering, University of South Florida, Tampa, Florida; [2]Mechanical Engineering, University of South Florida, Tampa, Florida.

Barium Strontium Titanate (BST) thin film is shown as a promising ferroelectric material for applications in tunable microwave devices like filters, phase shifters and resonators due to its high dielectric constant and large dependence of dielectric permittivity on the applied electric field. High tunability and low dielectric loss are desired for tunable microwave devices. The bottom electrode in parallel plate capacitor configuration is particularly challenging, since it should have high oxidation resistant at high growth temperatures and high conductivity. Though platinum is the most desirable metal electrode, hillock formation was observed after the deposition of BST thin film on $Pt/TiO_2/SiO_2/Si$. Epitaxial crystalline $SrRuO_3$ has been found useful as electrode due to its structural compatibility with ferroelectric material. $SrRuO_3$ was deposited using pulsed laser deposition (PLD) and film deposited at 600°C was highly crystalline. $Ba_{0.5}Sr_{0.5}TiO_3$ thin films were grown by PLD. $SrRuO_3$ deposited on top of the BST films was patterned using lithography technique in order to make the top electrode. The electrical measurements were achieved in the parallel plate capacitor configuration with $SrRuO_3$ as the top and bottom electrode. The microstructural and phase analysis of the BST films were performed using X-ray diffraction (XRD) method. XRD results show that the BST (100) peak is the most intense. The diffraction patterns are attributed to cubic (perovskite) crystal system. The analysis of surface morphology is done using atomic force and scanning electron microscopy. Results of structural and surface analysis, tunability and loss tangent as a function of deposition temperature, oxygen pressure and annealing temperature will be discussed. The optimization of tunability and dielectric loss of pulsed laser deposited BST thin films with Pt as the bottom electrode with different deposition conditions has been performed and the tunability of 3.1:1 and loss tangent of 0.0121 was achieved at 0.4− 0.6 GHz. The effects in tunability and loss tangent with $SrRuO_3$ as the electrodes will be analyzed and compared with Platinum electrodes.

3:15 PM G5.5
Dielectric Polarisation and Relaxor-Type Behaviour in $Sr_{1-x}Mn_xTiO_3$ Ceramics. Alexander Tkach, Paula Maria Vilarinho and Andrei Kholkin; Ceramics and Glass Eng., University of Aveiro, Aveiro, Portugal.

Strontium titanate (ST) is a quantum paraelectric / incipient ferroelectric. High dielectric tunability of ST is useful for high-frequency applications, where the resonance frequency can be shifted by moderate dc electric field. Pure ST do not exhibit ferroelectricity at temperatures as low as 0.035 K. There are several ways to induce the ferroelectric anomaly in ST by (i) application of electric field [1]; (ii) application of uniaxial stress [2]; (iii) isotope substitution of O anion [3], and (iv) substitution of Sr cation [4]. Namely, it has been shown that substitution of Sr for isovalent Ca, Ba and Pb induces a ferroelectric phase transition in $SrTiO_3$. Dielectric transition-like anomalies with remarkable frequency dispersion were obtained also by nonisovalent substitution of Sr for rare-earth ions and Bi. In this work, the effect of Mn substitution on the dielectric behaviour of ST ceramics is reported. $Sr_{1-x}Mn_xTiO_3$ ($x \leq 0.02$) ceramics were prepared by conventional solid-state method. The room temperature x-ray diffraction results indicated that all the samples are single cubic perovskite phase, and transmission electron microscopy (TEM) coupled with energy dispersive spectroscopy (EDS) analysis confirmed the incorporation of Mn into ST grains and the absence of any second crystalline phase until $x \leq 0.02$. Ferroelectric relaxor behaviour was found in $Sr_{1-x}Mn_xTiO_3$ ceramics. For x = 0.005-0.02, radio frequency dielectric measurements showed a maximum at 30-65 K, dependent on frequency and amount of Mn. The observation of hysteretic behaviour in the P vs E curves confirmed ferroelectricity of the low temperature phase and supported the ferroeletric relaxor-type evolution in $Sr_{1-x}Mn_xTiO_3$. The coexistence of ferroelectric and relaxor behaviour was attributed to a ferroelectric domain state induced by random fields. 1. P.A. Fleury, J.F. Scott, and J.M. Worlock: Phys. Rev. Lett. 21, 16 (1968). 2. H. Uwe and T. Sakudo: Phys. Rev. B 13, 271 (1976). 3. M. Itoh, R. Wang, Y. Inaguma, T. Yamaguchi, Y.J. Shan, T. Nakumura: Phys. Rev. Lett. 82, 3540 (1999). 4. V. V. Lemanov, Ferroelectrics 226, 133 (1999).

3:30 PM G5.6
Evolution of Anisotropic Elastic Strains, and Rf/Microwave Dielectric Properties of <110> Textured BST 60/40 Thin Films on <100> $NdGaO_3$ Substrates. William Kurt Simon, E. Koray Akdogan and Ahmad Safari; Ceramic and Materials Engineering Dept., Rutgers University, Piscataway, New Jersey.

BST 60/40 paraelectric thin films with <110> texture were deposited on <100> oriented $NdGaO_3$ substrates by pulsed-laser deposition. The effects of substrate induced anisotropic biaxial state of stress were studied by ultra-high resolution X-ray diffractometry. All independent elements of the 3D strain tensor, principal strains, principle directions and planes were determined as a function of film thickness in the range 20 to 1200 nm; and the variation of the elastic strain energy density is computed. The in-plane strains exhibit the largest change in magnitude as thickness increases, while the out of plane direction exhibits a modest decrease. The rocking curves of the films were modeled so as to gain further insight into the evolution of misfit dislocations. Permittivity, Q-factor, and tunability, were investigated in the 0.1-20 GHz range. Tunability at 10 GHz was determined to be around 40%, while Q-factors remained around 40. The nonlinearity in the dielectric response was found to be decreasing with decreasing thickness, and 100 nm thick films were found to be simply linear. The discussion is concluded with the possible origins of thickness dependent loss of nonlinearity in dielectric response.

3:45 PM G5.7
Microstructure-property relationships of $SrTiO_3$ thin films on epitaxial Pt electrodes for tunable microwave devices. Jiwei Lu, Sean Keane, Steffen Schmidt, Dmitri O. Klenov, Lia Bregante and Susanne Stemmer; Materials, University of California, Santa Barbara, California.

$SrTiO_3$ is a prototype, incipient ferroelectric with the perovskite structure. At low temperatures, $SrTiO_3$ shows a nonlinear, electric field tunable dielectric constant, which is of interest for tunable microwave devices operating at cryogenic temperatures. Perovskite films on metal electrodes typically are polycrystalline or textured. Their microstructures and the relationship to the dielectric properties are less well understood than those of epitaxial films. Pt is often used as an electrode in ferroelectric devices and integrated capacitors, due to its excellent chemical stability and good conductivity. To investigate the influence of the bottom electrode on the dielectric properties of $SrTiO_3$ films, we have grown epitaxial (111) oriented Pt films on sapphire substrates. Pt films grow with two orientation variants that are rotated in the film plane by 60° about the Pt [111] axis. We compare microstructures and low-temperature dielectric properties of $SrTiO_3$ films deposited by rf sputtering on as-deposited as well as annealed epitaxial Pt electrodes. Transmission electron microscopy (TEM) showed that all films contained (110) and (111) oriented grains, but grain sizes were larger on the annealed electrodes. We discuss the origin of the two $SrTiO_3$ film textures and present TEM studies of the changes in Pt electrode microstructures after annealing. At room temperature, $SrTiO_3$ films on heat-treated Pt showed a greater dielectric constant (261) and losses ($\tan \delta = 0.0021$), than those on the as-deposited Pt electrodes (238 and 0.0019, respectively). A low temperature loss peak around 250 K (at 1 MHz) was observed on both films and is likely responsible for the relatively high losses at room temperature. The origin of this loss peak will be discussed. At temperatures below the loss peak (190 K) $SrTiO_3$ films on annealed as well as as-deposited electrodes showed near intrinsic losses of 0.001 but showed different Curie-Weiss constants and temperatures. The dielectric behavior of the films was modeled for the different film textures using phenomenological theory and compared with the experimental results to extract the effects of the film microstructure on the dielectric properties. This research was supported by DOE office of Basic Energy Sciences (# DE-FG03-02ER45994).

4:00 PM G5.8
THz Time-Domain Spectroscopy of Ferroelectric Thin Films. Mukul Misra, Kenta Kotani, Iwao Kawayama, Hironaru Murakami and Masayoshi Tonouchi; Reserch Center for Superconductor Photonics, Osaka University, Suita, Osaka, Japan.

Displacive ferroelectric materials such as $SrTiO_3$ and $BaTiO_3$ have been very popular due to their very high dielectric constant and electrical tunability. Ferroelectric thin films offer a promising technology for electrically tunable frequency-agile devices. The ferroelectric properties of $SrTiO_3$ (STO), $BaTiO_3$ (BTO) and $Ba_xSr_{1-x}TiO_3$ (BSTO) thin films have been extensively studied for their application to microwave tunable filters, matching networks, phased array antennas and high-density dynamic random access memories. Recent developments in the technology for the less explored THz frequency spectrum got a lot of attention for the development of new generation THz devices for various applications. These thin films are a strong candidate for application to THz devices due to their high electro-optic coefficient, high dielectric constant, and tunability. The dielectric and optical response of these thin films differ significantly from that of the single crystal and strongly depends on the quality of thin film and therefore a systematic study of high quality thin films of these ferroelectric materials is required in THz frequency spectrum. We have grown very high quality STO, BTO and BSTO thin films by pulsed laser deposition (PLD) and measured of their temperature dependent dielectric properties in the THz frequencies. BTO and BSTO thin films of thickness about 1.0 μm and STO thin film of thickness 650 nm were deposited on MgO substrate. The dielectric and optical properties of thin films have been studied by THz time domain spectroscopy (THz-TDS) in the frequency range from 0.2 THz to 1.5 THz. Each thin film sample was mounted on the cold finger of a closed cycle cryo-cooler that facilitates the measurement in the temperature range from 20 K to 250 K. The sample was cooled down to minimum temperature (20 K) and THz waveforms after transmission through thin films substrate have been measured in time domain at various temperatures in warming run. Both real and imaginary parts of the dielectric constant of the thin films have been evaluated from measured waveforms. The temperature dependence of the dielectric constant of these films shows various transition temperatures that mainly corresponds to their phase transitions. At low temperatures, the measured frequency dispersion of the dielectric constant of STO thin film show Lorentzian oscillator behavior and softening of TO_1 phonon modes takes place with decrease in temperature and saturates near 60 K at the frequency 0.74 THz . The dielectric constant of BTO shows almost linear frequency dependence in the entire temperature range with a hump at nearly frequency about 0.45 THz that diminishes with increase in the temperature. The Real part of dielectric constant of BSTO thin film decreases from 100 GHz to 1.1 THz and shows a small peak at 1.1 THz and afterwards it increase with the increase in frequency.

4:15 PM G5.9
A High K Nanocomposite for High Density Chip-to-Package Interconnections. Taeyun Kim[1], Jayesh Nath[2], John Wilson[2], Stephen Mick[2], Paul D. Franzon[2], Michael B. Steer[2] and Angus I. Kingon[1]; [1]Materials Science and Engineering, North Carolina State Univeristy, Raleigh, North Carolina; [2]Electrical and Computer Engineering, North Carolina State Univeristy, Raleigh, North Carolina.

Increasing chip functionality demands a high density interconnect technology. One of the most commonly used interconnect technology uses a direct, contacting path for every input/output connection. This limits achievable density in pin and ball grid arrays and creates rework and compliance problems in very high-density solder bump arrays. AC-coupled interconnects is a very promising technology for achieving high-density interconnects while simultaneously providing a simple mechanical interface. In this technology buried solder bumps enable DC power and ground connections, and capacitors spaced across the same surface serves as the capacitively coupled interconnect for high frequency signals. Most implementations of the AC-coupled interconnect concept requires that the chip and the substrate be brought into close proximity (2-5 μm) to achieve the required capacitance for effective coupling. This requirement poses significant manufacturing and integration challenges due tolerance issues associated with such small dimensions. Hence there is a need for a high dielectric constant material that can achieve higher capacitance densities and relax the proximity requirements between the chip and the substrate. Such a material can also provide stress relief and thus improve the overall reliability of the interconnects. In this work the development of high K nanocomposite and its high frequency characterization has been presented. The dielectric properties and mechanical reliability of $BaTiO_3$ - epoxy composite thick films were evaluated for dielectric underfill in high frequency AC coupled interconnects. Bisphenol-A epoxy and a photosensitive epoxy were used for polymer matrix materials. 200 nm $BaTiO_3$ nano-powder was used for modulation of dielectric properties of underfill. Thermal behavior of underfill was evaluated by TGA and DSC, respectively. Dielectric properties were evaluated with ceramic loading and curing temperature. Mechanical reliability testing of underfill was performed on eutectic solder bumped Si substrates by tensile adhesion test as well as aging the part under 85/85 environment. The electrical properties were measured from 45 MHz up to 26.5 GHz. to evaluate its suitability for use in high density, high frequency interconnects. A floating parallel plate capacitor structure was used to extract the capacitance and quality factor of the capacitor over the frequencies of interest. The dielectric constant was found to be in the range of 35-40 and the Q factor of the capacitors was found to be 3 at 26.5 GHz. The high K nanocomposite shows relatively high dielectric constant compared to materials currently used (usually air or SiO_2) in capacitively coupled interconnects for chip-to-package communications. The loss was also found to be tolerable up to a frequency of 26.5 GHz and this should allow signaling well into the muti-gigabits range.

4:30 PM G5.10
Preparation of Nanocomposite Microwave Dielectric Films Using Aerosol Deposition Method and Their Dielectric Properties. Song-Min Nam[1,2], Naoko Mori[1], Mihoko Momotani[1], Hirofumi Kakemoto[1], Satoshi Wada[1], Jun Akedo[2] and Takaaki Tsurumi[1]; [1]Tokyo Institute of Technology, Tokyo, Japan; [2]AIST, Tsukuba, Japan.

In recent years, development of mobile electronic devices, such as cellular phones, personal digital assistants and notebook computers has been rapidly progressed so that microwave dielectric materials have been greatly paid attention to for filters, resonators, antennas operating at the microwave frequency ranges. For instance, perovskite ceramics with high permittivity, low dielectric loss and low temperature coefficient of the permittivity will be promising materials. Especially, the control of temperature coefficient of the permittivity will be a very important factor in microwave dielectrics because changes in dielectric permittivity caused by external environments are critical for the high frequency applications. Generally, barium- and strontium- based perovskites show positive and negative temperature coefficient of the permittivity, respectively, around room temperature. In this study, we focused on barium-, strontium-, calcium- based perovskite system as dielectric materials. If nano composite films can be fabricated at low temperature using the perovskite materials with different temperature coefficients of the permittivity, we can expect to control their temperature coefficients of the permittivity. So, we focused on the aerosol deposition method (ADM) which enables ceramic films with nanometer crystallite size to be grown at room temperature. Because the ADM is low temperature fabrication technology in nature, nano composite films with different temperature coefficients of the permittivity are expected. In the case of barium titanate films prepared by the ADM, their temperature coefficients of the permittivity showed positive as we expected, even though their permittivity was much lower than that of bulk barium titanate. We will discuss the dielectric properties of the nano composite microwave dielectric films fabricated by the ADM using the barium-, strontium-, calcium-based perovskite materials.

4:45 PM G5.11
Abstract Withdrawn

SESSION G6: MEMS & Integration
Chairs: Fred Roozeboom and Harrie A. C. Tilmans
Wednesday Morning, December 1, 2004
Liberty (Sheraton)

8:30 AM *G6.1
MEMS SiGe Technologies for RF and MillimeterWave Communications. Robert Plana, David Dubuc, Katia Grenier and Patrick Pons; LAAS-CNRS, Toulouse, France.

The information age is leading to a tremendous increase of the number of wireless applications devoted to personal and mobile communications, satellite communications, automotive applications, health control and survey environnment. This results to a spectrum overcrowding and a need for the future terminal to feature advanced performance in term of noise and linearity and more functionalities as reconfigurability and adaptability. In this context, the conventionnal approach that is used for many years for the microwave terminal is obsolete and the future architecture will have to involve both the MEMS technologies with SiGe technologies in order to assess the concept of smart systems. Different approach can be considered. The above IC approach where polymer layer are used to fabricate some passive components, the IN IC approach where using surface and bulk micromachining techniques, we are tailoring the performance of the circuit and system and the IPAD approach where the passive components are fabricated on the same substrate and the IC's are plugged to realized the desired functions. For each approach, it is important to assess the compatibility of the process with the integrated circuits. It will be presented the technological processes that have been developped to address all the approaches described and some demonstrators will be given to validate the concept. More precisely, low insertion loss filter in the 24 GHz will be presented followed by original antenna architecture surrounding the integrated circuits. A switch technology "above IC compatible will be presented. Finally, a bank of SiGe VCO will be presented allowing to synthesize signal from 2 GHz to 30 GHz that is a key component for reconfigurable front end. a full 24 GHz MEMS based transceiver will be presented illustrating the benefit of the MEMS SiGe concept.

9:00 AM G6.2
Novel laser transfer method for flexible electronic, photonic, and MEMS application. Il-Doo Kim[1], YongWoo Choi[2], Akintunde I. Akinwande[2] and Harry L. Tuller[1]; [1]Department of Materials Science and Engineering, MIT, Cambridge, Massachusetts; [2]Microsystem Technology Laboratory, MIT, Cambridge, Massachusetts.

Flexible substrates have advantages of light weight and improved resistance to impact damage, making them suitable for portable devices. There is a general interest in integrating active and passive electronic, electromechanical and photonic devices onto flexible substrates. A critical barrier towards realizing flexible systems is the high process temperatures normally associated with the fabrication of inorganic electronic and photonic devices. In order to solve this problem, we begin by fabricating the systems on rigid substrates followed by transfer to a flexible substrate. We utilize a laser transfer method in which films of interest are deposited by PLD onto high temperature durable transfer layers such as $La_{0.5}Sr_{0.5}CoO_3$ (LSCO) and $La_{0.5}Pb_{0.5}CoO_3$ (LPCO) films which in turn are deposited onto transparent substrates such as MgO and Quartz. For fabricating photonic and microwave devices, $BaTiO_3$(BT) and (Ba,Sr)TiO_3(BST) films were grown on a LSCO/(MgO, Quartz) substrate. The sample was attached to a flexible substrate such as ployimide. The BT and BST films on the transfer layer were separated from the rigid substrate by KrF excimer laser irradiation (248 nm, 15 ns) which passes through the transparent substrate and is absorbed by the transfer layer. Laser transfer was performed with various laser energy intensities (100 mJ 400 mJ) and repetition rates (1 Hz 50 Hz). The characterstics of $BaTiO_3$ waveguide and BST microwave tunable devices, prepared on flexible substrates, are discussed.

9:15 AM G6.3
Photodefinable Mixed Oxide Dielectrics II: Direct Fabrication of Patterned High-k Dielectrics for Low Cost RF Capacitive MEMS Switches. Clifford L. Henderson[1], Paul J. Roman[1], Augustin Jeyakumar[1], Abimbola Balogun[1], John Papapolymerou[2] and Guoan Wang[2]; [1]School of Chemical & Biomolecular Engineering, Georgia Institute of Technology, Atlanta, Georgia; [2]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia.

Low-cost MEMS switches are prime candidates to replace conventional GaAs FET and p-i-n diode switches used in RF and microwave communication systems due to their low insertion loss, good isolation, linear characteristics, and low power consumption. Various capacitive RF micromechanical switches made from a variety of metals have been reported in the literature for use in applications including phase shifters, reconfigurable filters, and tuners. The structure of these capacitive switches generally consists of a lower electrode, thin dielectric layer, and moveable membrane. Several studies have shown the importance of the dielectric layer in both switch performance and reliability. In most MEMS switches reported so far, this dielectric layer is typically silicon nitride deposited with PECVD or HDICP CVD techniques. Taking into account the higher costs and limitations associated with using CVD and sputtering techniques for switch fabrication, and the relatively poor dielectric properties of SiN, there is a need for lower cost fabrication methods that can be used to produce higher dielectric constant oxide structures for these MEMS devices. This paper presents an update concerning the novel methods we have recently developed for depositing the patterned dielectric layers required for capacitive MEMS switches. In this process, a photosensitive metal-organic precursor solution is used to coat the substrate and form a precursor thin film. Upon UV exposure, the organic ligands of the precursor molecules are cleaved which results in the formation of an amorphous metal oxide in the exposed areas. The remaining unexposed precursor material may be subsequently washed away using a developer solvent. Thus, the photosensitivity of these materials allows one to selectively deposit metal oxide structures without requiring the deposition of blanket oxides via CVD or other means, and it eliminates the need for subtractive plasma or wet etching. Previously we reported on the performance of our amorphous oxide dielectrics and RF MEMS switches made using these materials. In order to substantially increase switch performance and perhaps enhance reliability, we have been interested in developing methods to likewise deposit higher dielectric constant crystalline oxides for such applications. We have succeeded in developing such a method for producing patterned crystalline oxide dielectrics (e.g. perovskites) without the need for etching processes or high temperatures by using a combination of the photodefinable metal-organic systems and subsequent low temperature hydrothermal treatment. This paper will discuss our recent results in this area including physical and electrical characterization of the patterned crystalline oxides and results from the use of these materials in capacitive RF MEMS microwave switches.

9:30 AM G6.4
Novel High-Q Suspended Inductors on Alumina Ceramic Substrates. Lisa Woodward[1,2], Paul Woo[1], Mircea Capanu[1], Ivo Koutsaroff[1], C. R. Selvakumar[2] and Andrew Cervin-Lawry[1]; [1]Gennum Corporation, Burlington, Ontario, Canada; [2]Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada.

The growth of the wireless industry over the past ten years has created a need for good quality passive components, and in particular high-Q inductors. There has been a large amount of work aimed at improving the quality factors of inductors on both silicon and ceramic/insulating substrates. KAIST and other research groups have explored a MEMS technique, releasing the inductor coil to create an air gap between the coil and underpass, on silicon [1]. Typically the inductor coil has been separated by a 50 to 100μm air gap and has required special processing such as a dual exposure photoresist mold [1]. In the present work, suspended inductor coils have been fabricated and characterized on an alumina ceramic substrate [2]. The gap used was only 1μm and this was enough to increase the self-resonance frequency by up to 4GHz after release. The inductor coils were created in 6-10μm thick electroplated gold and the underpass in an aluminum layer. A sacrificial LPCVD oxide layer was used as the released dielectric. In the present study a range of inductance from 1 to 30nH was explored before and after release. The Q factors achieved in this work range from 40 to 70 in the 2 to 10 GHz range, which are some of the best Q factors reported for planar inductors in the literature (see Table I). In addition, since the architecture allowed the use of three metal layers, released transformers were also fabricated. They showed promising high frequency performance, which also will be presented. Minimum insertion loss better then -2dB was achieved between 10-12 GHz. The above described process is simple, precise, and manufacturable with the ability to extend the useful range of inductors to higher frequencies (1-10 GHz). [1] J.-B. Yoon et al, "CMOS-Compatible Surface Micromachined Suspended-Spiral Inductors for Multi-GHz Silicon RF Ics," IEEE Electron Device Lett., vol. 23, pp. 591-593, Oct. 2002. [2] A. Cervin Lawry at al, "Development of a Miniature Bluetooth Module for Manufacturability using a System-in-Package Approach," Ceramic Interconnect Technology: Next Generation, Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE), vol. 5231, pp. 7-11, 2003.

10:15 AM *G6.5
Communications and Sensor Technology and Systems at Millimeter Wave Frequencies. Jussi Tuovinen, MilliLab, VTT, Espoo, Finland.

Millimetre wave technology, which covers the frequency range from 30 to 300 GHz of the electromagnetic spectrum, has experienced a strong development period during the last decade. Submillimetre wave spectrum, in frequency above 300 GHz, has also become more mature, but does still lack significant commercial applications. Excluding recent imaging systems, practically all submm-wave applications are related to scientific or earth observation applications. Millimetre wave area on the other hand has several commercial applications and the technology, especially up to 100 GHz, is very similar to conventional microwave technology. Millimeter wave applications include radio links at different bands up 60 GHz, automotive radars at 77 GHz, Wireless Local Area Networks (WLAN), and radar and concealed weapon detection around 94 GHz. The development of monolithic microwave integrated circuits (MMIC) has been the main factor for the break-through of microwave and millimetre wave technology. Presently, these circuits can be produced up to about 220 GHz with indium phosphide based transistors, but as high as 300 GHz MMICs are foreseen to be available in the near future. Traditional gallium arsenide technology has been used up to 100 GHz. The development of metamorphic technology will reduce the cost of indium phosphide process, and therefore enables the commercial use of up to 200 GHz. The most interesting development area in semiconductor business from microwave perspective during past few years has been the Silicon Germanium (SiGe) technology. The fastest SiGe Hetero-junction Bipolar Transistors (HBT) have a cut-off frequency of 300 GHz. It can be seen that the SiGe technology will become a major competitor for GaAs in the microwave semiconductor market, because of lower cost and lower power consumption. From the reliability and yield point-of-view SiGe has also an advantage, because nowadays many SiGe foundries are running on higher volumes than GaAs foundries. However GaAs technology continues to have a well established position in power applications. There has been also strong interest in using CMOS and Low Temperature Co-fired Ceramic (LTCC) technology for RF and microwave components. Smart antennas have emerged as a key technology for third and higher generations of wireless communication systems because they add a new, spatial dimension to the currently used time, frequency, and code multiple access technologies. They offer an excellent and relatively inexpensive opportunity of increasing system capacity, number of users served, and quality of service. Smart antennas have an immediate impact on the efficient use of the spectrum, and also on the potential physiological impact on humans. This presentation describes millimetre and submillimetre wave applications for telecommunication and sensor systems with emphasis on specific needs and challenges related to materials.

10:45 AM *G6.6
High-Density, Low-loss MOS Decoupling Capacitors for integration with an RF Transceiver in a System-in-Package. Fred Roozeboom[1], Anton Kemmeren[1], Jan F. Verhoeven[1], Eric van den Heuvel[1], Johan Klootwijk[1], David Chevrie[2], Francois Le Cornec[2], Serge Bardy[2], Pascal Philippe[2], F. Murray[2] and Tomas Fric[3]; [1]Philips Research Labs, WAG02, Prof. Holstlaan 4, 5656 AA Eindhoven, Netherlands; [2]Philips Semiconductors, 2 Rue de la Girafe, F-14079 Caen, France; [3]Philips Semiconductors, Gerstweg 2, 6534 AE Nijmegen, Netherlands.

Recently the first highly integrated cellular RF transceiver systems were launched using Philips' new silicon-based System-in-Package (sbSiP) technology. This new technology utilizes back-end silicon processing to integrate passive components (particularly high-density capacitors) onto a silicon substrate that then acts as a carrier for active dies. A radio transceiver IC can be flip-chip mounted onto the passive silicon substrate, thus minimizing interconnect parasitics and footprint area [1]. This sub-assembly is then flipped back into a standard leadframe package. The passive die is made in the so-called PICS (Passive Integration Connecting Substrate) technology developed to integrate passive components such as high-Q inductors, resistors, accurate MIM capacitors and, in particular high-density (25 nF/mm2) MOS capacitors for decoupling and filtering. These capacitors are MOS 'trench' capacitors fabricated in macropore arrays that are dry-etched in silicon with pores of 1.5 um diameter and up to 30 um depth [2,3]. Capacitors with 30 nm ONO dielectric and poly-Si/ Al top electrode showed superior dielectric breakdown voltage (30 V typical) and very low leakage current density $<$ 1 nA/mm2 @ 22 V [3]. On die-level the MOS capacitors integrated in RF power amplifiers showed superior signal stability compared to identical test devices with discrete ceramic capacitors. This proves that these capacitors are very efficient in RF power supply decoupling and can be integrated with microwave subsystems in one package at low cost. A next step in the miniaturization is the use of so-called high-k oxides (HfO2, etc.), where we already have realized capacitance densities in excess of 100 nF/mm2. References 1. P. Philippe and A. Oruk, 'A Highly Miniaturized 2.4 GHz Bluetooth Radio utilizing an Advanced System-in-Package Technology', European Microwave Week, Oct. 11-15, 2004, Amsterdam; see also http://www.semiconductors.com/news/content/file_1044.html. 2. F. Roozeboom, R. Elfrink, T.G.S.M. Rijks, J. Verhoeven, A. Kemmeren and J. van den Meerakker, 'High-Density, Low-Loss MOS Capacitors for Integrated RF Decoupling', Int. J. Microcircuits and Electronic Packaging, 24 (3) (2001) pp. 182-196. 3. F. Roozeboom, A. Kemmeren, J. Verhoeven, F. van den Heuvel, H. Kretschman and T. Fric, 'High-Density, Low-loss MOS Decoupling Capacitors integrated in a GSM Power Amplifier', Mat. Res. Soc. Symp. Proc. 783 (2003) pp. 157-162 [paper B6.3].

11:15 AM G6.7
Direct Integration of AlGaAs/GaAs HEMTs on Ceramic Substrates for Super Hybrid Microwave ICs using Fluidic Self-Assembly. Ikuo Soga, Shoji Hayashi, Yutaka Ohno, Shigeru

Kishimoto, Koichi Maezawa and Takashi Mizutani; Nagoya University, Nagoya, Japan.

Recently, heterogeneous integration (HI) technology has been attracting much attention. It enables us to integrate devices made of various materials, for example, optical devices, high-performance InP HEMTs and SAW filters, onto various substrates. One of the most promising techniques for HI is the fluidic self-assembly (FSA) proposed by J. S. Smith et al. In the FSA technology, small device blocks separated from its substrate (epitaxial lift-off) are scattered on the tilted host substrate placed in fluid, then they slide and fall into recesses on the substrate. This technique has various advantages compared to heterogeneous epitaxial growth and wafer bonding. For example, this method is applicable to non-crystalline substrate materials, such as ceramics. In addition to this, the FSA process is very cost-effective due to the excellent efficiency of the material use, because the device blocks can be fabricated densely all over the guest wafer. We apply this technique to direct integration of HEMTs on ceramic substrates. Here, the device blocks consist of only a core part of the HEMT (without pads), the size of which is as small as a few tens of microns. This technology, we call it here the super hybrid integration technology, takes advantage of both monolithic and hybrid microwave ICs. A large parasitic inductance and capacitance due to the wiring between devices and ceramic substrate can be eliminated, because the standard planar-wiring process can be applied to the device blocks, which are arranged in the recesses with an accuracy of less than a few microns. Therefore, the ceramic substrate can be regarded as a large chip for an MMIC. Furthermore, the cost of the circuit should be much lowered because the expensive semiconductor area used is minimized. This paper discusses the process and performance of the AlGaAs/GaAs HEMTs integrated on an AlN ceramic. First, the HEMTs were fabricated on epitaxial layers grown on GaAs substrate. Next, the HEMT blocks were separated from the substrate by selective etching of the buried sacrificial layer (AlAs). The size of the device blocks, which have two fingers of 50-um gate width, was 87x57 um2. Then, the device blocks were arranged on the ceramic substrate using FSA. Finally, the process has completed by the BCB planalization and metal evaporation for wiring and pads. It has been demonstrated that the good FET characteristics were obtained even after FSA process.

11:30 AM G6.8
Die-on-Wafer and Wafer-Level Three-Dimensional (3D) Integration of Heterogeneous IC Technologies for RF-Microwave-Millimeter Applications. Jian-Qiang Lu, Siddharth Devarajan, Annie Y. Zeng, Ken Rose and Ronald J. Gutmann; Center for Integrated Electronics, Rensselaer Polytechnic Institute, Troy, New York.

Three-dimensional (3D) integration of heterogeneous IC technologies using through-die micron-sized vias is an attractive technology for high-performance RF-microwave-millimeter applications, especially where high manufacturing quantities are anticipated. This 3D integration technology requires die-to-wafer or wafer-to-wafer alignment, bonding, thinning and vertical inter-chip interconnection. A wafer-level technology platform is described, which bonds fully-processed, aligned wafers using a micron-thick dielectric adhesive, thins the top wafer in a three-step process and provides vertical interconnects with a copper damascene process. With this 3D technology, high Q passive components in a separate wafer (semiconductor is not required), high-performance analog-to-digital (A/D) converters and a RF transceiver IC in a second wafer, and a digital processing IC in a third wafer can be stacked and vertically interconnected through short inter-chip vias. Memory-only wafers can also be incorporated in the 3D system if needed. The technology is applicable to smart wireless terminals, millimeter phased array radars, and smart imagers. The presentation of this 3D heterogeneous integration approach will include design and simulation results, and a comparison with system-on-a-chip (SoC) and system-in-a-packaging (SiP) approaches.

11:45 AM G6.9
A Silicon Nitride Based Shallow Trench Isolation CMOS With Side-Gate for Integration With MEMS components for System-On-Chip Applications. Ali Gokirmak and Sandip Tiwari; Electrical and Computer Engineering, Cornell University, Ithaca, New York.

It has been demonstrated that micro-mechanical resonators have high quality factors making them good alternatives to conventional RF filters for system-on-chip applications for mobile communications. One of the major challenges to system-on-chip approach is the process integration of MEMS with CMOS circuitry. Fabrication processes of suspended structures like micro-mechanical resonators rely on extensive HF release etch of sacrificial SiO2 to release polysilicon structures. This requirement makes it very hard to integrate CMOS circuits utilizing SiO2 shallow trench isolation (STI) in close proximity to MEMS structures. One possible approach to overcome this problem is to use silicon nitride as the isolation material for shallow trench isolation instead of SiO2. Silicon nitride-silicon interface, however, has very high interface defect density leading to significantly high concentration of interface fixed charges. Interface fixed charges on the silicon sidewalls of the active areas of the MOSFETs lead to lower theshold voltage of the surface, leading to very high levels of drain to source and drain to substrate peripheral leakage currents. One possible way of reducing the leakage currents is to increase the substrate doping levels, which in return will increase the threshold voltage of the devices significantly. Another alternative would be to control all the relevant surfaces of the MOSFET with an additional gate surrounding the active area of the device. We have demonstrated excellent transistor characteristics by suppressing the peripheral leakage currents in silicon nitride isolated MOSFETs by employing an independently controlled side-gate, surrounding the active area of the devices. The surrounding side-gate, with the application of a negative bias for nMOSFET, increases the threshold voltage of the Si-STI interface, turning off the peripheral drain-to-source leakage currents. The negative potential on the side gate also keeps the p-type body of the device in accumulation, significantly reducing the Si-STI-interface-defect-assisted-peripheral-leakage components of the drain-to-substrate leakage of the pn+ junction. Our Nitride STI process is done by depositing thin silicon nitride, and n+ in-situ-doped polysilicon after the active area definition and etch. The polysilicon is patterned around the active areas with a lead to a contact area. STI process is completed by depositing thin silicon nitride and a thick layer of low stress nitride and chemical mechanical polishing of the wafers. Side-gated nMOSFETs fabricated with the nitride STI process show significantly high drive currents of up to 0.6mA/um, very good subthreshold slope of 80mV/dec, very minimal short channel effects; DIBL=21mV/V, and drain-to-source leakage below 5x10-14 A, leading to Imax/Imin >3.9e9, for Leff=0.23um , Weff= 0.29 um for channel doping of 1e17/cm3 and allow integration with micro-mechanical resonant structures.

SESSION G7: Ceramic Materials and Packaging
Chairs: Yong S. Cho and Takaaki Tsurumi
Wednesday Afternoon, December 1, 2004
Liberty (Sheraton)

1:30 PM *G7.1
Science-Based Processing Technology For LTCC Microelectronic Packaging. Kevin Ewsuk, Christopher DiAntonio and Markus Reiterer; Sandia National Laboratories, Albuquerque, New Mexico.

Multilayer ceramic technology offers a cost-effective and versatile approach to design and manufacture high performance and high reliability, three-dimensional (3D) microelectronic packages. However, there are technological challenges associated with the integration of functionally different materials into a 3D multilayer package. In particular, reproducible manufacturing of reliable multilayer ceramic packages requires processing control. A combination of practical experience and trial-and error are typically used to design and develop manufacturing processes for multilayer ceramic microelectronic packages; however an empirical engineering approach has limited application to new, more complex products. Manufacturing reproducibility and control can be achieved with statistical process control (SPC); however, this technology has limited application in the design and development of new processes for new products. Process control is required to design and manufacture high performance and high reliability multilayer microelectronic packages. Process control can be achieved through a combination of practical and science-based understanding. Science-based understanding is developed through modeling and characterization, and can be applied generally to a class of materials and processes. Together, science-based understanding and practical expertise can be applied to systematically develop more cost effective and more robust manufacturing processes. This paper focuses on master curve theory and its application to LTCC microelectronics packaging. Master curve theory, which utilizes analytical models based on fundamental theory, has practical application in the multilayer packaging industry to better understand and control the firing process (i.e., binder burnout and sintering). For process control, master curve theory in the form of the master decomposition curve (MDC) and the master sintering curve (MSC) have successfully been applied to predict and control binder burnout and sintering of LTCC dielectric tape, respectively. MSC theory also has been applied to assess lot-to-lot materials consistency and green process control/reproducibility in manufacturing. MSC theory has also been applied to assess process sensitivity. This science-based technology offers significant potential to improve the processes to manufacture microelectronic ceramic packages with improved dimensional control. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United

States Department of Energy under contract No. DE-AC04-94AL8500.

2:00 PM *G7.2
Bi_2O_3 - Nb_2O_5 Fluorite-Like LTCC Dielectrics. Matjaz Valant, Bostjan Jancar, Ursa Pirnat and Danilo Suvorov; Advanced Materials Department, Jozef Stefan Institute, Ljubljana, Slovenia.

Our analysis of the dielectric properties showed that the cubic fluorite solid solution of Bi_2O_3 and Nb_2O_5 exhibits a permittivity that is high enough for it to have the potential for use in LTCC technology (90). Unfortunately, however, the dielectric losses are too high and the temperature coefficient of resonant frequency is too negative for this kind of application. As well as this cubic solid solution, another tetragonal, fluorite-based modification was reported to appear in the same composition range (25 mol% of Nb_2O_5). It is evident from the literature that the conditions for the formation of this tetragonal phase are not understood and, therefore, neither a synthesis of the single-phase tetragonal ceramics nor their properties have been reported. We have investigated the nature of the cubic-to-tetragonal phase transition in order to determine the conditions for the synthesis. Our studies showed that the change in the crystal system is induced by a superstructural ordering. The order-disorder transition starts as homogeneous nucleation and is associated with the transformation from an incommensurate to a commensurate state. The order-disorder transition temperature was determined to increase with an increase in the Nb_2O_5 concentration. Studies of the influence of the ordering on the dielectric properties of Bi_2O_3 - Nb_2O_5 solid solutions show that the ordering reduces the dielectric losses and reverses the sign of the temperature coefficient of resonant frequency. The permittivity remains around 90. The temperature range over which the ordered tetragonal modification is stable coincides with the sintering temperatures of LTCC modules, and that opens up the possibility of using it in this technology.

2:30 PM G7.3
Microstructure and electrical properties of thick-film capacitor with low temperature fired Ba(Nd2-xSmx)Ti4O12 dielectrics. Li-Chun Chang and Bi-Shiou Chiou; EE, National Chiao Tung University, Hsinchu, Taiwan.

For high performance microelectronics and MEMS package, ceramics-based package are preferred over plastics. Low temperature co-fired ceramics (LTCC) technology is widely being employed in microwave applications. In this study, B2O3 and glass are employed to reduce the sintering temperature of Ba(Nd0.8Sm0.2)2Ti4O12 dielectric. Thick-film capacitors with Ba(Nd0.8Sm0.2)2Ti4O12 dielectric doped with low loss glass and/or low melting point oxide are prepared. The electrical properties and microstructure of the capacitors are correlated. The electrode/dielectric interfaces are observed. In this paper, the sintering behavior, phase evolution, interface reactions, and microwave dielectric properties are investigated. The microstructure of the electrode/dielectric interface has been investigated using scanning and transmission electron microscopy (SEM and TEM), and its correlation to the overall impedance has also been discussed.

3:15 PM *G7.4
Opportunities and Needs for Ceramic Materials in Wireless Communications. Terrell A. Vanderah, Ceramics Division, NIST, Gaithersburg, Maryland.

Ceramic materials serve critical enabling functions in both the high-power (e.g. base station infrastructure) and low-power (end-user devices) arenas of wireless technology. Attempts to predict future needs must be tempered with the economic uncertainties faced by the communications industry: Materials needed to enable and optimize next-generation applications will depend on the economic success of emerging approaches. One example is 3G telecommunications, which may require drastic infrastructural changes. What is certain is that wireless communications are here to stay and have markedly transformed society. An attempt will be made to describe generic technical needs – both near and long term – shaping the demands for new and/or improved ceramics, processes, and materials.

3:45 PM G7.5
Evaluation of Dielectric Permittivity of Barium Titanate Fine Powders. Takaaki Tsurumi, Takashi Sekine, Takuya Hoshina, Hirofumi Kakemoto and Satoshi Wada; Dept of Metallurgy and Ceramics Science, Tokyo Institute of Technology, Tokyo, Japan.

Barium titanate fine powders are being used for a raw material of multilayered ceramics capacitors (MLCCs) and for a filler in polymer composites for the embedded film capacitors. Selection of powders with a high permittivity is extremely important to achieve high performance in such devises. However, there is no effective method to evaluate dielectric permittivity of powders at present, therefore, the quality of powders has been evaluated after making devises, which markedly reduces the efficiency of the development. In this study, we have first proposed a reliable method to evaluate dielectric permittivity of powder itself. Our method uses a slurry as a sample of dielectric measurement and a finite element method to evaluate the permittivity of powder from that of slurry. Various barium titanate powders were supplied from manufacturing companies. Barium titanate powders were dispersed in a solvent of propylene carbonate using a ball mill and the dielectric permittivity of the slurry was measured at 20 MHz with a liquid measuring cell. The permittivity of the powder depended on its particle size, tetragonality and density. A statistical method was employed to explain the change in permittivity with these parameters.

4:00 PM G7.6
Temperature Dependent Dielectric Properties of Polycrystalline Aluminum Oxide and Aluminum Nitride Substrates. Liang-Yu Chen, OAI/NASA Glenn Research Center, Cleveland, Ohio.

Abstract Polycrystalline alumina (Al2O3) and aluminum nitride (AlN) have been used widely as high reliability substrate materials for electronic device packaging because of their superior stability and excellent electrical and thermomechanical properties. Recently, polycrystalline Al2O3 and AlN have been proposed and tested for high temperature electronic device packaging applications intended for operation at temperatures up to 500C. Therefore, the dielectric properties of these materials, including dielectric constants and effective bulk conductivities, at elevated temperatures are of interest, especially for RF applications. This article reports temperature dependent dielectric properties of polycrystalline 96% Al2O3 and AlN substrates from room temperature to 500C measured by AC impedance at 120 Hz, 1KHz, 10KHz, and 100 KHz. The dielectric constant of 96% Al2O3 was measured 9.5 at room temperature at all four frequencies. At 500C, the dielectric constant was 2.27 times of that at room temperature at 120Hz, and was 1.11 times of that at room temperature at 100KHz. At 120Hz, the effective bulk conductivity of 96% Al2O3 increased by four orders to 1.41E-7 S/m from 23C to 500C, but at 100KHz, it increased by only one order to 2.54E-6 S/m from room temperature to 500C. The relative dielectric constant of AlN increased from 8.95 at room temperature to 5344.6 at 500C at 120Hz, but at 100KHz it increased from 8.72 at room temperature to 115.0 at 500C. The effective bulk conductivity of AlN demonstrated negative temperature coefficient from 23 to 50C at all four frequencies. At 500C, the bulk conductivity increased by a factor of 3.3E4 from the 50C value of 2.65E-10 S/m at 120Hz, and increased by a factor of 1.1E4 from the 50C value of 8.86E-8 S/m at 100KHz. The temperature and frequency dependency on the quality factor and loss angle measurements will be discussed.

4:15 PM *G7.7
Ion Track Enabled Flexible PCB via Technology. Mikael Lindeberg, Hanna Yousef, Marek Skupinski, Chloe Bordas and Klas Hjort; Dept. Engineering Sci., Uppsala University, Uppsala, Sweden.

By combining ion track technology with ordinary low-resolution PCB lithography it is possible at low cost to create solid via connectors with high aspect ratios or bunches of submicron connector wires at a controlled small total cross-section at each via. We are demonstrating the technology with novel integrated PCB devices in two different flexible polyimide based foils (Espandex and Kapton HN), using the ultra high density vias and the submicron wires in applications like inductors, ferromagnetic resonance microwave filters and magnetoresistive sensors. Also, high-density bunches of submicron wires in via connectors may exhibit Litz-wire like behaviour, with no visible change in resistance at microwave frequencies. When a polymer foil is irradiated by swift heavy ions, a narrow linear latent track of pyrolysed material is created in the trajectory of each ion. The materials properties will differ between the track and the surrounding bulk and often the track can be etched with great selectivity. Since each ion creates such a track, the throughput is high enabling billions of well-defined linear pores through a foil at low costs. Commercial applications of ion track technology are large filters for ultrafiltration of biomolecules in applications like dialysis, clean water production and bacterial filtration of beverages. The costs of irradiation are around Euro 10 per sqm (with a density of 1 pore per square micron) for medium energy accelerators, and lower for low-energy accelerators. Hence, most of the production costs arise in the other process steps. In the last decade ion track filter membranes have been used as templates for electroplated or chemically synthesised nanowire production in science, using polymers that are rather easy to dissolve, e.g., polycarbonate. Also, the use of ion tracks has been demonstrated in flat panel display technology, omitting the high-resolution lithography step in submicron gates or field emitting. Our group is investigating the combined use of ion tracks in flexible PCB foils with low-resolution UV-lithography. The basic principle is to superimpose an etch anisotropy to the polymer with only a small change of its overall physical properties. Typically, the latent track that has undergone pyrolysis has a width of 10 nm, and is etched with selectivity from a few hundreds to a thousand times faster than the surrounding bulk. Hence, nearly cylindrical pores are created in the selective etch process. When the pores are etched for long they will start to merge together and finally a fully opened via is created. This process can be stopped at any moment, giving the desired porosity in the vias. Combining via connectors and submicron wires obtained by this way with lithographically patterned metal interconnectors on the foil, the above-mentioned devices are demonstrated.

4:45 PM G7.8
High Frequency Copper Migration Phenomena in Stress-Induced Phosphorus Mold Epoxy: an Electrochemical, Materials, and Package Model Analysis.
Surasit Chungpaiboonpatana[1,2] and Frank G. Shi[1]; [1]Chemical Engineering and Materials Science, University of California, Irvine, California; [2]Worldwide Manufacturing, Conexant (Mindspeed) Corp., Newport Beach, California.

The new paradigm shift in the back-end packaging and assembly industry is demanding environmentally friendly bleeding-edge materials. Accordingly, many Pb-free and Green (non-Halogen) materials are introduced to be incorporated into existing package varieties. Based on RoHS and EIA initiatives, the conversion of assembly materials into 100% non-hazardous components must be completed before the year 2006. Several previous studies have reviewed the implementation capability of different material combinations. However, they rarely address in detail the failure mode mechanism using these newly developed materials and seldom provide extensive failure analysis on the package model level. Furthermore, the challenges of higher product performance and package reliability requirements on any new chemistry and developed formulation are not fully examined. One new Pb-free/Green chemistry that causes significant industry concern is the P (Phosphorus) flame retardant particle for the epoxy mold compound. This P particle supports the UL flammability requirements and eliminates the use of hazardous Br (Bromine) and Sb (Antimony) based materials in the package component. But the presence of P produces a new failure mechanism of product leakage and/or short issues under specific operating conditions. Consequently, this study aims to develop a package level model and an understanding on the stress-induced Cu migration phenomena when the P particulates are present. The research is based on the electrochemical and failure mode analysis using active and high-frequency Si device designed for a large form factor package. First, the mold epoxy with embedded P particles is processed through JEDEC specified assembly and undergoes reliability stressings at the package qualification level. The various types of stressings and reliability conditions are exercised using TC, HTS, and biased-HAST with preconditionings to identify the mechanism of Cu migration when it is induced by the P particulates. Then, a detailed failure analysis on active modules is examined using SEM, EDX, continuity tests, fine-focused X-ray, and extensive parallel backlapping sequences to reveal the Cu migration path and its underlying mechanism. The study finds that Cu migration is induced by the stressed formation of phosphoric acid during specific biased and moisture related module applications, and its extension follows a non-coplanar pattern through the epoxy matrix. This research concludes with potential strategies for improvement, application-related modifications, and a detailed migration model obtained by comparing the analyzed failure mode mechanism, material properties, and electrochemically derived concept.