

Electronic Materials and Devices

Room 321/322 - Session EM-WeA

Diamond/Contacts to SiC

Moderator: J.P. Pelz, The Ohio State University

2:00pm EM-WeA1 Electron Transport Mechanisms in Thin B-doped CVD Diamond Films, J.E. Yater, A. Shih, J.E. Butler, P.E. Pehrsson, Naval Research Laboratory

Diamond possesses unique bulk and surface properties that can be exploited for electronic device applications. Of particular interest, diamond is a promising cold emitter material for vacuum electron devices because of the negative electron affinity (NEA) observed at specific surfaces. In this study, we use electron transmission measurements to examine the electron transport characteristics of NEA diamond. Specifically, we inject conduction electrons into thin CVD diamond films using a 0-20 keV electron gun, and we measure the intensity and energy distribution of low-energy electrons transmitted through the films. In measurements from films of varying thickness (0.15-5.0 microns) and B concentration, we observe two distinct transmission distributions. One distribution is consistent with emission from the diamond conduction band, with an energy spread of about 0.7 eV (although in some cases the distribution is affected by the doping properties). Transmission yields (i.e. number of transmitted electrons produced by each incident electron) are measured as high as 2-5 in this regime. The other distribution has an energy spread of about 3 eV with associated yields that are very low (~0.05). This distribution exhibits characteristics that are consistent with emission from graphitic material, and the energy distribution is relatively insensitive to the doping properties. An analysis of the data suggests that electron transport along graphite-containing grain boundaries is the primary transport mechanism when the electron escape distance is greater than 1 micron, while conduction band transport becomes increasingly dominant for transport distances less than 1 micron.

2:20pm EM-WeA2 On the Peculiarity of Depletion Layer in Diamond pn-junction, Y. Koide, National Institute for Materials Science (NIMS), Japan

The p-type Diamond has been easily obtained by doping with boron, and high-quality p-type diamond film was often grown on (100) diamond substrates by a microwave plasma-assisted chemical vapor deposition (MPCVD) technique. Recently, a growth method fabricating undeniable n-type diamond films was established by the MPCVD technique. The fabrication of the pn-junction structure widened a possibility of application of diamond to electronic and photonic devices. Therefore, understanding of characteristics of diamond pn-junction is our mandatory. Dependence of temperatures on carrier densities measured by Hall effect provided the ionization energies of P donor and B acceptor to be as large as 600 meV and 370 meV, respectively. Since both the dopants have deep nature, characteristics of the pn-junction are predicted to be very different from that of pn-junction which involves shallow dopants. The purpose of the present paper is, as a first step to understand the pn-junction physics of diamond, to analyze the deep dopant effect of the pn-junction involving deep P donor and B acceptor. The theoretical analysis will predict a limit of performance of diamond bipolar transistor, in which the deep nature of donor and acceptor will play an important role. The analysis of space charge and carrier profiles in the pn-junction was simply carried out by solving one-dimensional Poisson equation including compensation and carrier distribution. Profiles of ionized dopants and carriers in pn-junction of diamond with deep phosphorus donor and boron acceptor were calculated. Widths of depletion layer were around two times longer than those of space charge layer since there existed a transition region at the depletion layer edge. The difference between both the widths was reduced with increasing temperatures. It was predicted that a static saturation property of bipolar pnp-junction transistor was affected by the deep nature of dopants.

2:40pm EM-WeA3 Highly Conductive N-type Ultrananocrystalline Diamond: Materials Properties and Devices, J.E. Gerbi, O. Auciello, J. Birrell, Argonne National Laboratory; S. Curat, University College London, UK; D.M. Gruen, Argonne National Laboratory; R.B. Jackman, O.A. Williams, University College London, UK; J.A. Carlisle, Argonne National Laboratory
Ultrananocrystalline diamond (UNCD) is a fine-grained (3-5 nm) diamond material. Synthesized by MPCVD using Ar-rich Ar/CH₄ plasmas, the electronic, structural, and tribological film properties of UNCD can be tailored by doping with a controlled amount of N. These changes

correspond with clear transformations in the film structure, as both the grain size and grain boundary width of the UNCD films increase with nitrogen doping. In addition, we hypothesize that modifications in the bonding of the grain boundaries themselves occur. Together, these changes result in an n-type, highly conductive film that can retain the excellent tribological and structural properties of undoped UNCD. The conduction mechanism of nitrogen-doped UNCD is different than that of single-crystal diamond, with specific nitrogen-carbon and dangling bond complexes in the grain boundaries playing a crucial role. In this work, we discuss this unique conduction mechanism in the context of the UNCD film structure and growth process. We present recent device fabrication results and new Hall measurement results, performed with a field switching setup at variable temperatures, which provide incontrovertible evidence of the n-type conduction and significant mobilities of this material. For example, a film grown with the relatively low nitrogen doping level of ~ 0.2 at.% displays an electron carrier concentration of ~ 5 x 10¹⁷ cm⁻³ and a mobility of greater than 6 cm²/Vs, while retaining the excellent tribological, chemical, and structural characteristics necessary for conductive MEMS/NEMS and bioelectronics applications. Films with much higher conductivities and doping concentrations can also be produced; doping levels as high as 1.1 at. % N will also be discussed in the context of thin-film diamond electronics. This work was supported by the DOE-Office of Science-Materials Science under Contract No. W-31-109-ENG-38.

3:00pm EM-WeA4 Raman Spectroscopy of Ultrananocrystalline Diamond Thin Films, J. Birrell, J.E. Gerbi, O. Auciello, Argonne National Laboratory; J. Johnson, X. Xiao, Argonne National Laboratory, U.S.; J.A. Carlisle, Argonne National Laboratory

Raman spectroscopy is often used as an efficient and non-destructive way of determining the bonding structure of diamond thin films. However, interpretation of the Raman spectrum of carbon materials with small grain sizes and a large number of grain boundaries, such as in nanocrystalline, ultrananocrystalline (UNCD), and amorphous diamond, is not straightforward. In order to correctly interpret the Raman spectral features of UNCD thin films, a series of films spanning the range of structures from microcrystalline to UNCD was studied using visible and UV Raman spectroscopy, as well as scanning and transmission electron microscopy. For UNCD, we find that although the sample has been found to be composed of ~95% sp³-bonded carbon by other techniques including near-edge adsorption fine structure (NEXAFS) and TEM, none of the spectral features observed using visible Raman spectroscopy can be attributed to sp³-bonded carbon. As the UNCD grains appear purely crystalline in TEM, we identify the disordered carbon at the grain boundaries of UNCD as responsible for all spectral features observed. This enables us to probe the grain boundary structure of UNCD specifically, which is of great utility for understanding the electronic and structural properties of the material. Finally, we interpret the changes in the Raman spectra of UNCD grown under various growth conditions, including low temperature growth; as well as with nitrogen doped UNCD, which results in a large increase in the conductivity of UNCD films. This work was supported by the DOE-Office of Science-Materials Science under Contract No. W-31-109-ENG-38.

3:20pm EM-WeA5 Silicon on Diamond Technology, A. Aleksov, N. Govindaraju, F. Okuzumi, G.N. Yushin, North Carolina State University; S.D. Wolter, J.T. Prater, Army Research Office / AMSRL-RO-PM; Z. Sitar, North Carolina State University

The roadmap for the development of Si-based high-speed low-power electronics for digital applications shows that Moore's law predicting an exponential increase in the speed operation of digital ICs will remain valid in the near future, yielding ever shrinking devices and larger integration scales, necessitates a decrease of the supply voltage to limit the loss power and an increase in the complexity of heat management. Silicon on Diamond (SOD) is proposed as an alternative to SOI to overcome the severe thermal limitations imposed by SOI, but at the same time retain the advantages of SOI in respect to increased device speed and carrier confinement. SOD technology is beneficial for both digital Si-applications as well as for high-power high-frequency Si-devices. This technology utilizes the unique physical properties of diamond i.e. the highest thermal conductivity (up to 22 W/cmK) and a high specific resistance (10¹² Ωcm range). In our SOD approach, the insulating layer is a highly-oriented diamond (HOD) film with bulk-like properties, which can be grown on large area Si substrates. Following the diamond growth, another Si wafer is bonded to the diamond in UHV at a pressure of around 32 MPa and a temperature of 950°C. The bonded Si wafer is then thinned to the desired thickness. The

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bonded interface has been studied by TEM and EELS to assess structural and chemical character of the interface, respectively. Metal strip heater devices fabricated on SOD samples confirm the heat spreading efficiency of the diamond layer and benefits of SOD. For comparison, the same device structures have been fabricated on a SOI wafer. The experimental results are accompanied by finite element thermal simulations of the experimental set ups enabling the direct comparison of theoretical and experimental data.

3:40pm EM-WeA6 Metallizing a Semiconductor Surface with Hydrogen, P.G. Soukiasian, V. Derycke, Commissariat à l'Energie Atomique, France; F. Amy, Y.J. Chabal, Agere Systems; M. D'angelo, H. Enriquez, V.Yu. Aristov, M. Silly, Commissariat à l'Energie Atomique, France; M. Pedio, P. Perfetti, Istituto di Struttura della Materia, Italy

Passivation of semiconductor surfaces against chemical attacks can be achieved by terminating the surface-dangling bonds with a monovalent atom such as hydrogen. Such passivation has invariably leads to the removal of all surface states in the band gap, and thus to the termination of non-metallic surfaces. Here, the first observation of semiconductor surface metallization induced by atomic hydrogen is reported. This surprising result, established using atom resolved scanning tunneling microscopy (STM) and spectroscopy (STS), core level and valence band photoelectron spectroscopy (XPS,UPS) and multiple reflection infrared absorption spectroscopy (MR-IRAS) is achieved on the Si-terminated 3C-SiC(100) 3x2 cubic silicon carbide surface. The metallization is evidenced through band gap closing in STS, Fermi level built-up in UPS and specific related spectral features in MR-IRAS. In addition, core level photoemission spectroscopy using synchrotron radiation gives fine details about interatomic charge transfers within the surface and sub-surface regions. The metallization process results from competition between hydrogen termination of surface dangling bonds and hydrogen-generated steric hindrance below the surface. Understanding the ingredient for hydrogen-stabilized metallisation directly impacts the ability to eliminate electronic defects at semiconductor interfaces critical for microelectronics, provides means to develop electrical contacts on high band-gap chemically passive materials, particularly exciting for interfacing with biological systems, and gives control of surfaces for lubrication, e.g. of nanomechanical devices. @FootnoteText@ @footnote 1@ V. Derycke, P. Soukiasian, F. Amy, Y.J. Chabal, M. D'angelo, H. Enriquez and M. Silly, Nature Materials 2, 253 (2003).

4:00pm EM-WeA7 Macroscopic and Microscopic Electronic Behavior of Cubic Inclusions in 4H-SiC, K.-B. Park, Y. Ding, J.P. Pelz, The Ohio State University; K.C. Palle, M.K. Mikhov, B.J. Skromme, Arizona State University; A. Los, M.S. Mazzola, Mississippi State University

Double-stacking-fault cubic inclusions in n-type 4H-SiC@footnote 1@ were studied with ballistic electron emission microscopy (BEEM) in ultra high vacuum where the inclusions intersect a Pt/SiC Schottky barrier (SB) interface. We confirmed prior proposals@footnote 2@ that the inclusions behave as quantum wells, and found a propagating two-dimensional quantum well conduction band minimum (CBM) at ~0.53 eV below the CBM of the bulk 4H-SiC host. This agrees well with calculations of the quantum well state@footnote 3@ and is close to the SB height lowering found with macroscopic I-V and C-V measurements.@footnote 4@ The macroscopic C-V SB heights were found to be quite similar to macroscopic I-V measurements, which is interesting because less than 5% of the Pt/SiC interface is on the low-barrier-height inclusions. We believe this similarity between C-V, I-V, and BEEM measurements can be explained by the actual SBH of the inclusions at the Pt/SiC interface, along with changing occupation of the quantum well states away from the interface during C-V measurements. We are currently developing electrostatic modeling to quantify this hypothesis. We will also discuss the first "hole BEEM" measurements of SiC on a Pt/p-type 4H-SiC (presently without inclusions) SB interface. We found a 1.40 eV p-type SB height, compared with 1.54 eV of Pt on n-type 4H-SiC, as well as a double threshold, suggesting a possible second valence band maximum. @FootnoteText@@footnote 1@R. S. Okojie, M. Zhang, P. Pirouz, S. Tumakha, G. Jessen, and L. J. Brillson, Appl. Phys. Lett. 79, 3056 (2001).@footnote 2@T. A. Kuhr, J. Q. Liu, H. J. Chung, M. Skowronski, and F. Szmulowicz, J. Appl. Phys. 92, 5863 (2002).@footnote 3@H. Iwata, U. Lindefelt, S. Oberg, and P. Briddon, J. Phys. C 14, 12733 (2002).@footnote 4@B. J. Skromme, K. Palle, C. D. Poweleit, L. R. Bryant, W. M. Vetter, M. Dudley, K. Moore, and T. Gehoski, Mater. Sci. Forum 389-393, 455 (2002).

4:20pm EM-WeA8 Improved Titanium / Nickel Ohmic Contacts on N-Type 4H Silicon Carbide, J.H. Park, P.H. Holloway, University of Florida

Nickel (Ni) contacts are the most commonly used ohmic contacts to n-type silicon carbide (SiC). Unfortunately, the Ni contacts exhibit rough interface morphology after high temperature annealing. In addition, the reaction to form the silicide liberates carbon, which can segregate to the metal-semiconductor interface. These two factors limit the reliability of the Ni contacts to n-SiC for high temperature and power applications. The electrical and structural properties of electron-beam evaporated nickel/titanium metal contacts to n-type 4H SiC were studied by current-voltage (I-V), Auger electron spectroscopy (AES), secondary ion mass spectrometry (SIMS) and X-ray diffraction (XRD) techniques. Nickel/titanium metal contacts on the 4H SiC were rectifying as deposited but turned to ohmic after rapid thermal annealing (RTA) at 1000°C for 2 minutes in nitrogen. The nickel/titanium contacts were converted to the layer sequence of titanium carbide/nickel silicide/SiC by annealing. This structure had a low specific contact resistance of 10@super -5@ @ohm@-cm@super 2@. A shallower and smoother nickel silicide/SiC interface was obtained as compared to the conventional only-nickel contacts. The nickel silicide layer was formed on SiC by a nickel-SiC reaction during high temperature annealing which left excess carbon at the interface between the silicide and SiC. Titanium reacted with the carbon to form a titanium carbide layer on the nickel silicide, which led to reduced carbon excesses at the interface and lower resistance of the ohmic contacts. The phase inverting mechanisms and the effects of nickel/titanium thickness on this process have been studied. Phase analysis of the nickel silicides and titanium carbides using XRD and TEM will be reported.

4:40pm EM-WeA9 Correlation Between Electrical and Microstructural Properties of Low Resistance TiAl-based Ohmic Contacts to p-type 4H-SiC, S. Tsukimoto, K. Nitta, M. Moriyama, M. Murakami, Kyoto University, Japan

In order to understand a contact formation mechanism for TiAl-based contacts, the electrical properties and microstructure of conventional Ti/Al and recently developed Ni/Ti/Al ohmic contacts to p-type 4H-SiC were correlated. The Ti/Al and Ni/Ti/Al ohmic contacts were prepared by depositing sequentially Ni, Ti, and Al on the SiC substrates doped with Al at 4.5x10@super 18@cm@super -3@, and subsequently annealing in an ultra high vacuum at 1000°C for 2min and 800°C for 10min, respectively. These contacts provided the lowest contact resistances of 1x10@super -5@ and 7x10@super -5@ @ohm@-cm@super 2@, respectively. X-ray diffraction and cross-sectional transmission electron microscopy were used to identify reacted layers formed at the ohmic contacts/SiC interfaces. For the Ti/Al contacts, ternary Ti@sub 3@SiC@sub 2@ compound layers with a hexagonal structure were formed to grow epitaxially on the substrates. For the Ni/Ti/Al contacts, hexagonal Al@sub 4@C@sub 3@ compound layers were also formed to grow epitaxially on the SiC in addition to other binary compounds. The formation of these epitaxial carbide layers was found to have a strong influence on the contact resistances to the SiC, and was essential to prepare low resistance TiAl-based contacts. The present experiment indicated that both the Ti@sub 3@SiC@sub 2@ and the Al@sub 4@C@sub 3@ layers played a role of intermediate semiconductor layers (ISL) between p-type SiC and the contact metals, which reduced the barrier height and/or depletion region.

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