Hasselt Diamond Workshop 2019-SBDD XXIV

SBDD XXIV was held at cultuurcentrum Hasselt (ccHa) Belgium on 13-15 March 2019. This conference focuses on the progress in science and applications of CVD diamond with emphasis on application of diamond in different technologies such as quantum, high-power electronics and energy applications. There were more than 45 presentations and 115 posters overall with close to 200 participants. Majority of talks at the conference were on the NV centre. However, a good number of talks were about devices and the use of diamond as a heat spreader. Few of the talks and posters which I found very interesting has been explained below.

Selected Presentations:

Diamond/h-BN heterostructure for high-performance electronic devices (*Yamaguchi Takahide, University of Tsukuba, JAPAN***)**

The presenter demonstrated diamond FETs with a monocrystalline hexagonal boron nitride(h-BN) as a gate dielectric. h-BN crystal was cleaved and laminated on the hydrogen-terminated diamond surface. The diamond which is known for stable physical and chemical stabilities plus the advantage of nitrogen vacancies which are suitable for quantum processing and nanoscale sensing was used together with h-BN which has added the advantage of the low density of charged impurities and high carrier mobilities (>300 $cm^2V^2s^{-1}$). The lattice mismatch between diamond and h-BN is relatively small which further makes this integration better. Ti/Pt metal contacts on the oxygen-terminated diamond were used as a platform to exfoliate h-BN (17nm thick), and the good interface was demonstrated using TEM. The p-type FET showed 30mA/mm of Id max with around 3Kohm channel resistance which is beneficial for realizing low energy loss electronics. They also reported mobilities of 300 $cm^2V^2s^{-1}$ for moderately high carrier density of $5x10^{12}$ cm^{-2}. Shubnikov-de-Hass oscillations were observed in the magnetoresistance at lower temperatures because of enhanced mobility. Further, these oscillations were used to calculate carrier density, effective mass and quantum scattering time. These oscillations were proof of the hole gas estimated at the interface of h-BN and diamond.

The high thermal conductivity of h-BN (4W/cm*K) was shown as added advantage plus the layer acts an oxidant resistant up to 100°C which makes it a promising candidate for high power electronics. This study also opens the door for the study of fundamental properties of charge carriers in diamond.

Diamond Deep depletion MOSFET (*Cedric Masante, University of Toulouse, CNRS, FRANCE***)**

The speaker showed an improved version of Diamond Deep depletion MOSFET; these devices have much better ohmic contacts and processing. Majority of diamond MOSFETs have been developed based on surface transfer doping concept on the hydrogen-terminated diamond and have faced issues such as low channel mobility and the bad interface between oxide and diamond.

1b diamond plate is used as a base with 400 nm thick p-type channel layer on which selectively heavily doped p-type layer was grown for ohmic contacts followed by Ti/Pt/Au metal stack. They used 50nm Al_2O_3 deposited using atomic layer deposition as a gate oxide. Based on good quality oxide they could achieve leakage measurements Ion/Ioff of 10^5 at 250°C. The higher ionization energy of boron acceptors (38 meV) made the conductivity of the channel temperature dependant, and the made the operating temperature of these MOSFET to be around >150°C. Improved ohmic contact process in this work made the specific On resistance to be 50mΩ at 250°C which is significantly better than previously reported values. These samples, however, showed lower breakdown voltage of -175V than the previous values probably due to interface charges and quality of oxide.

Sub-mm thick diamond layer on aluminium nitride for thermal management applications (*Soumen Mandal, Cardiff university, Cardiff, U.K.***)**

The author demonstrated the possibility of thick diamond films growth on aluminium nitride layers. Current need for higher power and frequency devices demands better efficient heat extraction technologies, and currently majority of these technologies use silicon carbide which has thermal conductivity of 360 – 490 W/m K. In recent time diamond which has the highest known thermal conductivity of 2100 W/m K has been found to be most suitable candidate for replacing silicon carbide. For efficient heat extraction, it is important that the diamond layer is at least 50-100 micron thick to be able to extract all the heat away. While the growth of thin diamond on GaN is possible growing a thicker diamond is difficult given that the absence of any covalent bond between diamond and GaN. The possible way is to use an intermediate layer which is silicon nitride. However, poor thermal boundary resistance harms the advantage of the diamond layer.

The speaker introduced the use of Aluminium nitride (AlN) as an intermediate layer and demonstrated the growth of > 100-micron thick diamond layer. They grew diamond on AlN seeded with H-terminated seeds and showed excellent layer qualities with good measured thermal boundary resistance, however; they also highlighted that the H-terminated seeds are needed to achieve high seed density on AlN surface and O-terminated seeds make the thicker diamond films possible. This was studied by using Zeta potential of the AlN surface which was found negative along with O-terminated seeds and positive for H-terminated seeds. For growth of O-terminated seeds pre-treatment of H_2/N_2 gas was used.

Inkjet-printed high- Q nanocrystalline diamond resonators (*Adre F Sartori, Delft University of Technology, CD Delft, NETHERLANDS***)**

This was one of the coolest work presented at this conference which demonstrated the fabrication of functional, high-performance diamond-based micro-sensors by using inkjet printers. Diamond has been one of the most desirable candidates for various electronics and sensing devices, and its extreme properties and robustness makes it even suitable for mass sensors and filters.

The author showed a lithography-free, low-cost method of fabrication of diamond-based micro resonators which were achieved using a modified desktop inkjet printer. They managed to locally deposit with good precision up to 50-60 um spots which were further grown into around 1um thick nanocrystalline diamond films using hot filament chemical vapour deposition systems. They used Reactive ion etching further to suspend these structures.

The resonant frequency of around 9-30 MHz with a quality factor exceeding 10^4 was shown for these resonators. These structures were analysed using laser interferometry which is based on the Doppler effect. These resonators as mass sensors yielded mass responsivities up to 981

Hz fg^{-1} after Au deposition, and ultrahigh mass resolution up to 278 ± 48 zg, which is much higher than most of the resonators fabricated using traditional top-down etching process. Data analysis in controlled atmospheres were shown with a clear dependence of Q-factors on gas pressure up until 1 atm. Of all the talks presented at this conference, this was one of the most visually impressive consisting of several colourful images and live demonstrations.

Integrated diamond heat spreaders for GaN power devices (*R Soleimanzadeh, POWERlab, EPFL, SWITZERLAND***)**

This work used diamond for high power vertical GaN on silicon devices and was interesting since the work I presented at this conference uses a similar approach but for RF devices. In this work, the author demonstrated the use of diamond heat spreaders on top of vertical GaN high power PIN diodes and showed a comparison of different size, thickness and thermal conductivity. They presented both experimental and theoretical comparison of all these parameters.

The authors used a very different approach for this work, conventionally an intermediate layer is used to the grown diamond on GaN which is either Silicon nitride or aluminium nitride as discussed before. In this work, they used nano diamond particles as the seeding layer and used high-level gas purity (N6.0) to obtain good quality diamond layers and managed to obtain large grain sizes as well. However, they later added silicon nitride as an adhesion layer to GaN and were able to minimise thermal boundary resistance. They showed up to 2um thick diamond layer held using electroplated copper pads; this part of their work wasn't very clearly discussed.

The thermal characterization of the devices fabricated using these heat spreaders showed significant cooling and almost 50% reduction in thermal resistance. The authors also raised concerns on the increase in leakage and reduction in breakdown after the whole process which was related to processing issues, and they appeared hopeful of tacking these issues in the next generation of devices.

Superconducting diamond on silicon Nitride for device applications (*Henry Bland, Cardiff University, Cardiff, U.K.***)**

Superconducting boron-doped diamond grown using chemical vapour deposition has been well knowing for use as cryogenic detectors. The authors showed the need and demonstrated its growth on silicon nitride.

They investigated first the pre-seeding treatments and studied their effect on the silicon nitride substrate. The surface of silicon nitride was studied after exposure to oxygen plasma and compared to relatively known techniques like RCA and solvent clean. They also used zeta potential as a function of pH to assure that substrate and seeds have opposite polarity. This is essential to obtain self-assembly of monolayer diamond particles. Compared to another process the RCA process showed the least negative zeta potential across the measured pH range. Further, they also performed XPS measurements to determine the composition of the nitride surface after these processes.

After these treatments boron-doped diamond was grown and characterised using SEM and Raman. They demonstrated pin-holes on the samples with RCA clean which was expected based on zeta potential and XPS data. Resistivity measurements showed improvement from RCA to solvent clean and an oxygen plasma process. The discussion with authors gave the impression that many efforts are being put into making proper devices soon using these substrates.

Electrical field study into the depth of a diamond Schottky diode by Electron Beam Induced Current (*Juliette Letellier, University Grenoble Alpes, CNRS, FRANCE)*

This study was attractive as it demonstrated a new approach to examine in depth characterization in the Z direction while the electrical measurements are carried out for a Schottky contact on a diamond layer. This is important to understand the electric field into the stack of diamond layer which has been a long pending question.

This work showed combing growth along with fabrication and electrical techniques to achieve an understanding of electric field underneath the Schottky contact. Schottky diode using heavily doped p++ layer on top of HPHT substrate was used on top of which > 20um non intentionally doped p- layer was grown. This was further polished to remove lateral overgrowth followed by Ti/Au metal attack as contacts.

Electron beam induced current measurements were further performed on these samples up to 600V in reverse bias and an electric field was mapped out. The hot spots observed were used to understand the electrically active defects.

Takuya Murooka from the same group also showed results on the investigation of leakage current sites in diamond pn junctions. They showed the usefulness of electron beam induced current (EBIC) as a tool for understanding defects in diamond Schottky contacts and understanding the electrical field profiles.

My contribution was an oral presentation on Performance evaluation of ultra-thin GaN-on-Diamond RF transistors. GaN-HEMT RF devices are increasingly adopted in commercial and aerospace markets. Its high electron sheet density and velocity makes them exceptional RF devices; however thermal challenges now limit the performance. Diamond with its highest known bulk thermal conductivity has been demonstrated as a good choice for heat management, and therefore it makes an ideal candidate for integration with GaN. This work presented successful integration of ultra-thin (354nm) GaN layers-on-Diamond in an RF device with excellent power performance at 1GHz. Intensive electrical characterization and photoluminescence (PL) studies showed good electrical and thermal performance. Thinning down the GaN brings the diamond close to the active heat region making it more efficient and good electrical performance validates that quality of GaN wasn’t compromised during the thinning down process.

Concluding remarks

I am grateful to the UKNC for providing me with the financial support that made my participation possible at this conference. This was a great opportunity to listen to talks ranging from fundamental and application-driven viewpoints discussed at the highest level. Discussion during oral presentations and posters were fruitful for further understanding and will help me immensely in the planning of my next experiments.