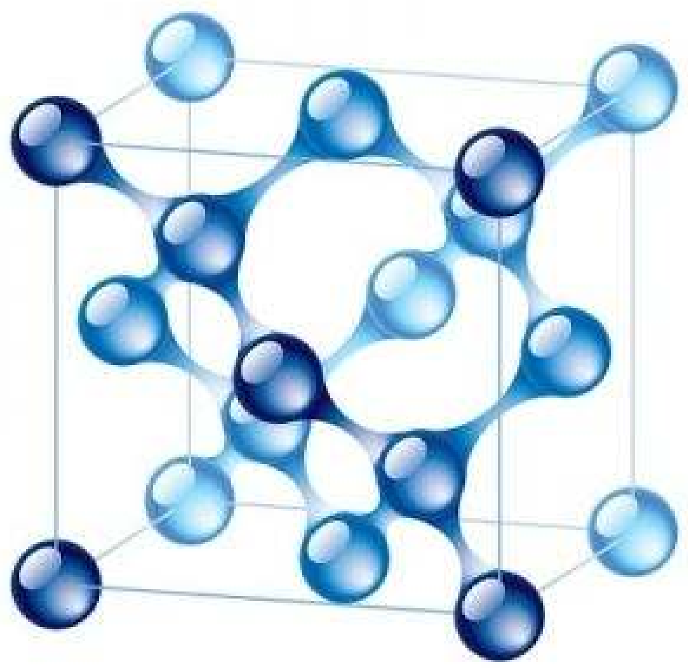

Diamond Detectors Development and Applications

2nd RBI Detector Workshop

Plitvice Lakes, 7 - 10 May 2012, Croatia

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PROGRAMME AND BOOK OF ABSTRACTS

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Ruđer Bošković Institute, Zagreb, Croatia

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Particle detectors

Ministry of science education and sports of the Republic of Croatia

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Dear Participants,

Welcome to the 2nd Detector Workshop organized by the Experimental Physics Division of the Ruđer Bošković Institute (RBI). Taking into account long lasting tradition in development of radiation detectors at RBI, since it has been founded in 1950, and a fact that detectors are very important tools in many research fields of physics and other sciences, we have decided to organize biannually workshops devoted to some particular topic related to development and/or applications of these devices. The first Workshop was organized in 2010 under the auspices of the European Union Seventh Framework Programme (FP7) through the project *SPIRIT.* It was devoted to new detector technologies for materials research using ion beam analysis (IBA). Since IBA techniques are very well recognized among other nuclear techniques and since these represent very important application of small accelerators, the first Workshop attracted many senior and young researchers from many European countries.

The second Workshop is organized with the support from two projects, namely the FP7 project *Particle Detectors*, and the project '*Development of high energy ion microbeam technology for novel applications of diamond'* within the *Strategic Japanese-Croatian Cooperative Program on Materials*. We decided to focus the subject of the present Workshop to the development of diamond detectors, since this topic corresponds excellent to the interests of both of these projects, with the great potential to attract the attendance of European and Japanese researchers active in the field and contribute to implementation of both projects.

The objectives of the FP7 project *Particle detectors* (coordinator Tome Antičić - RBI) related to diamond detectors are to reinforce the potential and capability for the development of state-of-the-art diamond detectors for charged particles detection in nuclear, high energy physics and applications and to enhance the available capabilities for testing of these detectors at the RBI accelerator complex. This project also aims to strengthen the RBI strategic partnerships with prominent EU research entities and to enhance the exchange of the know-how and experience with diamond researchers from the prominent laboratories of EU and worldwide. We hope that this Workshop will make significant contribution in this respect.

The main research objective of the Japanese-Croatian project (principal investigators: Tomihiro Kamiya - JAEA and Milko Jakšić - RBI) is development of new type of transmission particle diamond detector with high sensitivity for detection of single ions. The project also aims to study different applications of diamond irradiation by ion beams, such as studies of diamond radiation hardness and fabrication of graphitic micro-structures by heavy ion microbeams done in collaboration with University of Torino. At the Workshop first results obtained under this project will be presented by Japanese and Croatian researchers, as well as by associate partners.

To conclude, we are confident that scientific programme of the Workshop will stimulate discussions and perhaps new collaborations and projects and therefore the organizers wish you pleasant and enjoyable time at the Plitvice lakes national park and Croatia.

Milko Jakšić, Tome Antičić and Mladen Kiš

WORKSHOP PROGRAMME

Monday, 7th May			
Afternoon		Transfers from Zagreb airport to Plitvice lakes	
20:00		Welcome reception	
20:30	Jadranka Barešić	Plitvice Lakes - the Karst Phenomena of Tufa Barriers Formation	
Tuesday, 8th May			
8:30	Milko Jakšić, Tome Antičić	Workshop introduction	
Session I - Charge transport in diamond			
Chair: Milko Jakšić			
8:45	James Butler	CVD Diamond Growth and Surface Chemistry	
9:30	Mara Bruzzi	Radiation induced defects in diamond	
10:00	Ettore Vittone	Characterization of electronic transport properties in detectors by IBIC	
10:30 - 11:00		**Coffee Break**	
Session II - Characterisation of radiation damage in diamond			
Chair: Ettore Vittone			
11:00	Željko Pastuović	IBIC characterization of focused ion beam induced radiation damage in semiconductor detectors	
11:30	Takeshi Ohshima	Observation of transient currents induced in semiconductor diodes by heavy ion incidence using time resolved IBIC	
12:00	Vladimir Cindro	Diamond sensors in radiation-harsh environment - ATLAS experiment	
12:30	Annika Lohstroh	Effects of fast neutrons on the performance of diamond detectors	
13:00 - 17:00		**Lunch, free time**	
Session I and II - contributed talks			
Chair: Mladen Kiš			
17:00	Ivana Capan	Electrically active defects in semiconductors induced by radiation	
17:30	Hendrik Jansen	Charge collection in scCVD diamond at cold to ultra-cold temperatures	
18:00	Wataru Kada	Transient Ion-Beam-Induced Current Analysis of Thin Film CVD Diamond Detector	
18:20	Ivana Zamboni	Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions	
18:40	Veljko Grilj	Irradiation of thin diamond detectors and radiation hardness tests using MeV protons	
19:00 - 20:30		**Dinner**	

Wednesday, 9th May			
Session III - Radiation hard detectors for high energy physics and applications			
Chair: Tome Antičić			
9:00	Tomihiro Kamiya	Applications of diamond as an ion transmission detector	
9:30	Alexander Oh	3D diamond detectors	
10:00	Eleni Berderman	Particle detectors based on Diamond-on-Iridium structures - Advantage and perspectives	
10:30-11:00		**Coffee Break**	
11:00	Mladen Kiš	Ultra fast timing using diamond detectors	
Session IV - Diamond and radiation - other applications			
Chair: Tomihiro Kamiya			
11:30	Michal Pomorski	Super-thin scCVD membrane detectors for X-ray beam monitoring at modern light sources	
12:00	Paolo Olivero	Applications of ion microbeam lithography in diamond	
12:30	Sebastien Pezzagna	Colour centers in diamond by ion implantation	
13:00 - 17:00		**Lunch, free time**	
Session III and IV - contributed talks			
Chair: Takeshi Ohshima			
17:00	Fabio Schirru	Fabrication and Characterization of Graphite Electrodes for Diamond X-ray Dosemeters	
17:30	Natko Skukan	Time Resolved Ion Beam Induced Current on Single Crystal Diamond Detector	
17:50	Shinobu Onoda	Single Ion Detection by Ion Beam Induced Luminescence from Diamond Containing NV Centers	
18:20	Federico Picollo	Focused Ion Beam Fabrication of a Diamond Detector with Buried Graphitic Electrodes	
18:40	Jacopo Forneris	Sharing of Anomalous Polarity Pulses in a Ion Beam Micromachined Multi-electrode Diamond Detector	
20:00		**Workshop dinner**	
Thursday, 10th May			
8:30		Transfer from Plitvice lakes to Zagreb	
8:00 - 11:00		FP7 Project Particle Detectors – Project Steering Committee meeting	

Session I - Charge transport in diamond

I-1 CVD diamond growth and surface chemistry

James Butler

U.S. Naval Research Laboratory, Washington, USA – Retired

Smithsonian Institution National Museum of Natural History Research, Washington, USA – Associate

In the last decade, chemical vapor deposition (CVD) of diamond has matured to the point of producing materials purer, more perfect, and of more consistent quality than naturally available diamond, and thus enabling applications exploiting the solid state properties of diamond. Defects/dopants strongly influence the solid state properties of diamond and the resultant devices. This talk will review our current understanding of the CVD growth mechanisms, relevant surface chemistry, and defect formation with the goal of providing a better understanding of CVD diamond materials to the solid state physics community.

I-2 Radiation-induced defects in diamond

Mara Bruzzi

INFN – University of Florence, Firenze, Italy

The discovery of diamond synthesis by Chemical Vapour diamond (CVD) in early 1980s opened a large range of new applications for diamond: one of the most promising is the use of diamond in electronic devices and sensors. Due to the highest reported value of displacement energy, together with its wide band gap, diamond is intrinsically radiation tolerant: it has been thus proposed as particle detector and radiation dosimeter in nuclear and high energy physics applications. Nevertheless, as a wide band gap semiconductor material, both native and radiation-induced defects can influence strongly its optoelectronic performances, giving rise to unwanted trapping-detrapping and polarization effects limiting its efficiency. Unfortunately, a thorough model of radiation damage of these devices in terms of main responsible defects is still lacking, due to the difficulty to apply traditional experimental methods on such kind of material. A review is proposed on main results in this field.

I-3 Characterization of electronic transport properties in detectors by IBIC

EttoreVittone

Physics Department and NIS Excellence Centre – University of Torino; INFN –sez.Torino; CNISM –sez. Torino; via P. Giuria 1, 10125 Torino, Italy

The acronym IBIC (ion beam induced charge) was coined in the early 1990s to indicate a scanning microscopy technique which uses MeV ion beams as probes to image the basic electronic properties of semiconductor materials and devices. Since then, IBIC has become a widespread analytical technique to characterize materials for electronics or for radiation detection by virtue of the valuable information it can provide on charge transport phenomena occurring in finished devices, not easily obtainable by other analytical techniques.

In this talk significant examples of IBIC applications, mainly focused on diamond detectors and other wide band gap semiconductors, will be given in order to illustrate the potential of the technique both to map and to profile the charge collection efficiency and carrier lifetimes.

Session II - Characterisation of radiation damage in diamond

II-1 IBIC characterization of focused ion beam induced radiation damage in semiconductor detectors

Željko Pastuović

Australian Nuclear Science and Technology Organisation, Locked bag 2001, Kirrawee DC NSW 2232, Australia

The overview of the extensive radiation damage studies in silicon semiconductor detectors exposed to a focused ion beam (FIB) irradiation will be given, including both experimental and simulated data. Particular focus will be given on 3 interrelated ingredients of our studies:

i) experimental protocol suitable for various materials and devices;

ii) qualitative/quantitative analysis of the results and

iii) developed theoretical model for interpretation of acquired radiation damage data.

The outcomes of silicon radiation damage studies will be discussed in detail. The lessons learned on silicon serve as the initial platform for the radiation hardness testing and comparison of the other materials used for fabrication of semiconductor detectors. Preliminary results for the radiation hardness of diamond detectors obtained by IBIC will be presented and discussed.

II-2 Observation of transient currents induced in semiconductor diodes by heavy ion incidence using time resolved IBIC

Takeshi Ohshima, S. Onoda, T. Makino, N. Iwamoto, M. Deki, W. Kada,T. Kamiya

Japan Atomic Energy Agency, 1233 Watanuki, Takasaki, Gunma 370-1292, Japan

Ion Beam Induced Charge (IBIC) is a useful technique to evaluate the quality of particle detectors. However, ions introduced into detectors as probes create crystal damage in detectors and as a result, their Charge Collection Efficiency (CCE) decreases with increasing damage. For the accurate evaluation of the detector quality, it is important to measure CCE values without the degradation of their characteristics due to damage creation. Single ion hitting Transient Ion Beam Induced Current (TIBIC) technique can solve this issue because charge induced by an ion incidence can be detected. In this study, using a TIBIC system installed at JAEA Takasaki, we measured charge induced in silicon (Si), silicon carbide (SiC) and diamond diodes by heavy ion incidence such as oxygen, silicon, gold ions with MeV range energies.

II-3 Diamond sensors in radiation-harsh environment – ATLAS experiment

Vladimir Cindro

Jozef Stefan Institute, Jadranska 39, SL-1000 Ljubljana,Slovenia

Polycrystalline diamond sensors are used in single particle counting mode in Beam Conditions Monitor built as a part of ATLAS experiment at Large Hadron Collider at CERN. Radiation hardness, operation at room temperature and excellent time resolution were key points for the choice of diamonds as sensor material. They have exhibited excellent stability during the first two years of operation in radiation harsh environment. Total fluence of 10^{15} particles/cm^2 is expected after several years of operation. Ionization current induced in diamond sensors by charged particles in Beam Loss Monitor is used to measure the flux of off-beam particles near the collision point.

II-4 Effects of fast neutrons on the performance of diamond detectors

Annika Lohstroh, S. Gkoumas, P.J. Sellin

Department of Physics, Member of the South East Physics Network, SEPnet, University of Surrey,Guildford,UK

Diamond is one of the hardest materials known to mankind, due to the high bonding energy between the atoms that constitute its tight lattice structure, that has one of the highest atomic densities of any material under standard conditions. Due to this strong bonds, diamond is expected to be more resiliant to radiation damage - so called radiation hard - compared to other semiconductor materials. Through the last decade, electronic grade single crystal bulk material with excellent electronic properties has become available commercially and high performance has been demonstrated for heavy particle spectroscopy and timing. Hence there is large interest to apply detectors based on this material in high radiation flux environments. We have studied the degradation of diamond detector performance and change in change transport properties, through particle spectroscopy as well as temperature dependent X-ray induced current experiments after fast neutron irradiation and subsequent annealing. These measurements are complemented by optical characterisation. The charge carrier mobility did hardly change with irradiation dose, so the reduction in charge collection efficiency is attributed to a decrease in carrier lifetime, which is expected due to the creation of additional defect levels. Cathodoluminescence reveals a reduction in Band A luminescence, and some radiation induced signatures.

C-1 Electrically active defects in semiconductors induced by radiation

Ivana Capan

Ruđer Bošković Institute, Division of Materials Physics, HR-10002 Zagreb, Croatia

Ion implantation has been and still is one of the most important techniques for device fabrication. Of key interest are defect clusters associated with implantation. Since those clusters change the electrical properties of material it is important to understand and control their formation. Studying these defects by techniques which average over a substantial volume is virtually impossible. In this study we have used damage produced by fast (reactor) neutrons to simulate aspects of ion implantation damage. In this way we hope to produce defects which are similar to those produced in ion implantation but which are uniformly distributed over a sufficiently large volume to facilitate measurements. Moreover, we will present fundamental differences between electron, neutron irradiation and ion implantation damage.

C-2 Charge collection in scCVD diamond at cold to ultra-cold temperatures

Hendrik Jansen[1], D. Dobos[1], H. Pernegger[1], V. Eremin[2], N. Wermes[3]

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[2]*IOFFE Physico-Technical Institute of Russian Academy of Science, St. Petersburg, Russia*

[3]*University of Bonn, Nussallee 12, 53115 Bonn, Germany*

For the new series of triplet magnets, the Beam Instrumentation Group seeks a detector concept for a Beam Loss Monitor that provides full functionality at ultra-cold temperatures (1.9 K). A fast response time, excellent radiation hardness, long durability and reliability, good SNR, and a broad dynamic range are all critical properties. An obvious candidate for the sensor material is single-crystal Chemical-Vapour-Deposited (scCVD) diamond.

A set-up for Transient Current Technique (TCT) measurements for CVD diamond detectors at ultra-cold temperatures has been put in place at CERN. Helium cooling allows for temperatures down to 1.9 K. Am-241 and Sr-90 sources provide ionizing radiation. Broad-band read-out electronics and a current-sensitive amplifier enable measurement of the transient current.

We will present results of measurements of the temperature dependence of fundamental diamond quantities such as carrier drift mobility and velocity, total charge yield, lifetime and detrapping time constants, and trapping energy levels. Furthermore, the difference in charge collection between MIP-signals and α-signals is shown and important results for possible detector operations are derived. A model capable of explaining parts of the data - the plasma effect with associated recombination, trapping and detrapping - will be presented for scCVD diamonds.

C-3 Transient ion-beam-induced current analysis of thin film CVD diamond detector

Wataru Kada, T. Satoh, N. Iwamoto, S. Onoda, T. Makino, M. Koka, T. Ohshima, T. Kamiya
Japan Atomic Energy Agency, 1233 Watanuki, Takasaki, Gunma 370-1292, Japan

Thin film Transmission diamond detector is now under development for the detection of single-ion-hit of MeV energy range ions generated from AVF cyclotron at JAEA/Takasaki. To check the response behavior of the detector, pulsed charge signals were obtained by using alpha particle checking sources. However, the radiation hardness of the detector is also need to be investigated on the actual microbeam irradiation environment. The effect of the damage produced on the impact of high-energy heavy ions was evaluated by using Transient Ion Beam Induced Current (TIBIC) analysis system [1]. The differences in the signals obtained before- and after the intense microbeam irradiation on the area of 50 × 50 μm^2 through the comparison of the peak current and integral total charges of each single pulses induced by the single ion hit of 15MeV O^{4+}.

[1] J.S. Laird, T. Hirao, H. Mori, S. Onoda, T. Kamiya, H. Itoh, Nucl. Instr. Meth. B 181(2001) 87

C-4 Radiation hardness of single crystal CVD diamond detector tested with MeV energy ions

Ivana Zamboni[1], Ž. Pastuović[2], M. Jakšić[1]
[1]*Ruđer Bošković Institute, Division of Experimental Physics, HR-10002 Zagreb, Croatia*
[2]*Australian Nuclear Science and Technology Organisation, Locked bag 2001, Kirrawee DC NSW 2232, Australia*

The spectroscopic properties of a commercial high purity single crystal diamond detector (1 mm^2 area, 500 µm thickness)have been studied using focused ion beams (H, He and C ions) in the MeV energy range. A measured relative energy resolution of 1.3% (FWHM=25 keV)for detection of 2 MeV protons demonstrated useful spectroscopic performance of the CVD diamond device for light ion/atom detection. In order to test diamond radiation hardness the detector was selectively irradiated with 6.5 MeV focused carbon beam up to fluencies of 10^{11} ions/cm^2. A reliable measurement of ion fluences was accomplished by usage of the microprobe single ion technique – IBIC (ion beam induced charge). After irradiations meant to produce selectively damaged regions in the diamond, low current mode IBIC was additionally used to monitor the degradation of the charge collection efficiency (CCE) and spectroscopic properties of the device. In order to get better overview of the detector performance after irradiation, different ions with ranges smaller, equal and larger than the depth of produced damage were used as IBIC probes. The same experimental procedure of irradiation and IBIC imaging has been performed on a detector grade silicon PIN diode in order to make direct comparison of diamond and silicon material radiation hardness. Contrary to the approved radiation hardness of diamond detectors used in high energy physics experiments, presented results show that diamond compared to silicon is less radiation hard for the spectroscopy of short range heavy ions.

C-5 Radiation hardness of scCVD diamond detector irradiated by low energy protons

Veljko Grilj[1], M. Jakšić[1], W. Kada[2], T. Kamiya[2], N. Skukan[1]

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[2]Japan Atomic Energy Agency, 1233 Watanuki, Takasaki, Gunma 370-1292, Japan

Radiation tolerance of 50 µm thick transmission scCVD diamond detector has been investigated by irradiating detector with 4.5 MeV protons. Heavy ion microprobe system allowed for selective damage introduction in 50×50 μm^2 area. Charge collection efficiency (CCE) degradation due to produced electrically active defects was monitored online by ion beam induced current (IBIC) technique. Irradiation was stopped when approximately 3% signal reduction was observed. For comparison, 50 µm thick silicon SB detector was exposed to proton microbeam using the same procedure until nearly the same CCE decrease was noticed. Additional IBIC maps for both detectors were obtained with 2 MeV protons as an IBIC probe for diamond detector and 1.3 MeV protons as an IBIC probe for silicon detector. Results surprisingly show significantly lower radiation tolerance of diamond detector compared to the silicon one.

[1] M. Franklin et al., Nucl. Instr. and Meth. A 315 (1992) 39
[2] W. Adam et al., Nucl. Instr. and Meth. A 476 (2002) 686
[3] W. de Boer et al., Phys. Stat. Sol. A 204 (2007) 3004

Session III - Radiation hard detectors for high energy physics and applications

III-1 Applications of diamond as an ion transmission detector

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In the ion beam facility, TIARA of Atomic Energy Agency (JAEA), an ion microbeam system was developed for a study on irradiation effects of living cells which were hit by the heavy ions with the total energy of hundreds MeV. In order to perform cell irradiation in the atmosphere using high energy heavy ions more accurately and more efficiently, the single ion hit system was proposed to be equipped with the thin film vacuum windows which act as a transmission type particle detector. Diamond films were tested as the detectors for this purpose, because they have enough mechanical strength to be thin vacuum windows as well as the characteristic as a wide band-gap semiconductor which can operate with low noise in room temperature and also under lighting of optical microscope observation.

III-2 3D diamond detectors

Alexander Oh

University of Manchester, Manchester, UK

Diamond is an established detector material with good radiation resistance, while 3D detector read-out geometry is a well established technique to increase the radiation hardness of Silicon particle detectors. The combination of 3D read-out geometry with diamond as a detector material is a promising approach to provide very radiation resistant particle detectors.

The talk presents first studies of towards the fabrication of 3D diamond detectors. Graphitic electrodes have been implanted into bulk diamond with laser patterning, and first results obtained with synchrotron radiation show a good response.

III-3 Particle detectors based on Diamond-on-Iridium structures – Advantages and perspectives

Eleni Berdermann[1], M. Ciobanu[1,2], J. Frühauf[1], M. Kiš[1,3], W. Koenig[1], P. Moritz[1], M. Schreck[4], C. Stehl[4], MD. S. Rahman[1], M. Träger[1]

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[4]*University of Augsburg, Augsburg, Germany*

We report on the preparation and characterization of novel, large-area, 'quasi single crystal' diamond detectors grown by CVD on four-inch multilayer substrates of the type Ir/YSZ/Si001. We compare the detector characteristics of recent Dia-on-Ir (DOI) samples to those of spectroscopic-grade homoepitaxial CVD-diamond films grown on HPHT single-crystal diamond substrates, and to ultra-fast polycrystalline diamond plates grown on silicon wafers. The present results let us expect wafer-scale diamond detectors, which combine high charge-collection efficiency and good energy resolution with excellent particle timing and counting properties. This provides hitherto unrivaled possibilities for the detector instrumentation of future nuclear and particle physics experiments.

Session IV - Diamond and radiation - other applications

IV-1 Ultra fast timing using diamond detectors

Mladen Kiš

Ruđer Bošković Institute, Division of Experimental Physics, HR-10002 Zagreb, Croatia

Present and even more so future nuclear and particle physics experiments are aspiring top performance covering all aspects along the experiments realization. Here the diamond detectors (DD) are entering in some of the applications as a performance-optimized solution. In this presentation we will discuss the use of the DDs in time measurements giving few examples of design and application. We will particularly address the use of DD in time measurement of the minimum ionizing particles also from the point of the fast signal processing and the electronics design.

IV-2 Super-thin scCVD membrane detectors for X-ray beam monitoring at modern light sources

Michal Pomorski

CEA, LIST, Diamond Sensor Laboratory, CEA/Saclay, 91191 Gif sur Yvette,France

Diamond is the preferred solid state material for producing thin (<5micron) membrane position sensitive detectors for low energy X-ray beam monitoring (XBPM): above the silicon K edge, diamond has about ten times higher X-ray transmission than silicon; diamond has effectively zero thermal leakage current; and correctly made diamond devices do not degrade under X-ray beam irradiation. Commercially available thin membranes (3-4 microns) are made of polycrystalline CVD (pcCVD) thin films. Due to the presence of grain boundaries in pcCVD diamond such detectors fail in terms of position measurement, when micro-beams are used or when single particle detection mode is involved. Furthermore, due to the inhomogeneous charge traps distribution, the charge collection varies significantly with the interaction position in these detectors, thus energy loss spectroscopy cannot be performed. Here, for the first time, we propose to use the single crystal CVD diamond as a thin-membrane (1-10 microns) XBPM. Using Ar/O plasma etching it is possible to produce self-supported scCVD membranes (windows) of a size approaching initial size of the scCVD sample. After metallization and contacting, electrical properties of XBPM membranes were probed with 5.5MeV alpha-particles and X-ray beam. scCVD membrane detectors exhibit: stable operation, charge collection efficiency close to 100% with homogenous response, and extraordinary dielectric strength up to 30V/micron.

IV-3 Applications of ion microbeam lithography in diamond

P. Olivero

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MeV and keV ions represent a powerful tool for fabrication and functionalization of diamond, particularly if it is considered that the structural modification of the diamond crystal offers access to alternative allotropic forms of carbon (diamond, amorphous carbon, graphite) with significantly different physical properties.

In the present report a general overview will be given on the research activity on the development of ion-beam micro-fabrication techniques in single-crystal diamond carried at the University of Torino in collaboration with partner institutions in the framework of several ongoing funded projects.

Particular focus will be given on the opportunities offered by deep ion beam lithography for the functionalization of the electrical, optical and structural properties of diamond, and key results obtained in collaboration with partner ion microbeam facilities will be reported.

IV-4 Colour centers in diamond by ion implantation

Jan Meijer[1], K. Groot-Berning[1], A. Lohrmann[1], I. Dobrinets[3], M. Leska[1,2], S. Pezzagna[1], A. Zaitsev[3], J.F. Roch[2]

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Individual nitrogen-vacancy (NV) optical centers in diamond are believed to be used in anticipated quantum photonic and optoelectronic devices. It is believed that the NV centers could work as registers in quantum computers, single photon sources in quantum communication systems, or ultrasensitive magnetic sensors. For instance, it has been shown that a single NV center allows the measurements of magnetic field with nT precisions [1]. As the NV center is a point defect of an atomic size, it is suitable for applications at sub-nanoscale. A unique feature of the NV centers is the dependence of their optical properties on the charge state, the most important of which are neutral (NV^0) and negative (NV^-) ones. The maintenance of the charge state of the NV centers can be well achieved by the termination of diamond surface with hydrogen for the NV^0 state, or oxygen for the NV^- state [2]. The different charge states of the NV centers can be easily selectively addressed spectroscopically.

Single NV^- centers possess an exceptional functionality. They allow an optical readout of the Fermi level position, monitoring of diffusion of individual atoms, or indirect measurements of mobility and lifetime of the charge carriers. Using the ion implantation techniques, it is possible to controllably manipulate and address individual NV centers with a very high precision. Now it is at a 10 nm scale and may even reach a sub-nanometer range with the recently developed techniques [3]. In particular, the achievements in the super resolution imaging based on stimulated emission depletion (STED) microscopy may provide monitoring of the implantation of single atoms and formation of individual NV centers.

In this presentation, we compare different approaches aimed at addressing single optical centers and show the status and prospects of new sensor techniques.

[1] J.R. Maze et al. Nature 455 (2008) 644

[2] Grotz et al., Nature Communications 3 (2012) 729

[3] S. Pezzagna et al., SMALL 6 (2010)2117

C-6 X-ray induced photocurrent characteristics of polycrystalline CVD diamond detectors with different amorphous carbon electrodes

Fabio Schirru[1], A. Lohstroh[1], K. D. G. I. Jayawardena[2], S. J. Henley[2], and P.J. Sellin[1]
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[2]*Advanced Technology Institute, University of Surrey, Guildford, UK*

We present the X-ray detection characteristics of a polycrystalline electronic grade CVD diamond sensor prepared in house with four electric contacts per side in a sandwich configuration. One side had Al/Au contacts produced by sputtering deposition while the opposite side had amorphous carbon electrodes fabricated by Pulsed Laser Deposition (PLD) technique in the fluence range of 2.3 – 3.6 J/cm^2. In order to investigate the dosimetric properties of the different carbon electrodes, the device was then irradiated with a 50 kV$_p$ X-ray tube with a molybdenum reflection target.

Results showed no dependence of the dosimetric properties of the device respect the different nature of the carbon electrodes. Faster dynamic response and better stability of the signals were achieved for applied bias up to 50 V with signal to noise ratio (SNR) of ~ 300. In all cases, the induced photocurrent presents also a linear dependence respect to the dose rate.

C-7 Time resolved ion beam induced current on single crystal diamond detector

Natko Skukan, V. Grilj, M. Jakšić
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Ion beam induced charge (IBIC) is a powerful tool for characterization of electronic properties in different semiconductors and insulators. Its extension to time resolved IBIC (TRIBIC) gives better insight to physics of the charge carriers' transport inside the device under test. Microprobe system at RBI Zagreb has a capability of running TRIBIC experiments using light and heavy ions with spatial resolution better than 1 µm. 50 ohm wideband RF amplifiers are mounted in vacuum chamber in close proximity to the sample. Signals are collected with a 5 GHz LeCroy Wavemaster 8500A digital oscilloscope using software developed in LabView environment. TRIBIC setup in lateral mode was used to record charge transient signals between the two electrodes of 1x1x0.5 mm Diamond Detectors Ltd. single crystal CVD diamond sample. We report on preliminary results of the experiment and possibility of use of scCVD diamond detectors as position sensitive devices together with excellent timing properties of such devices.

C-8 Single ion detection by ion beam induced luminescence from diamond containing NV centers

Shinobu Onoda[1], H. Abe[1], T. Yamamoto[1], T. Ohshima[1], J. Isoya[2], T. Teraji[3], K. Watanabe[3]
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We are developing the Ion Photon Emission Microscopy (IPEM) system at JAEA/Takasaki. The IPEM technique gives us two-dimensional (2D) maps of Single Event Effects (SEEs) on a microelectronics circuit. The powerful advantage of 2D map is the ability to determine the position dependence of SEEs due to a single ion incidence. To observe 2D map by IPEM, the position where the single ion strikes a scintillator placed over a microelectronics circuit is recorded together with the single ion induced event. Since the spatial resolution is determined by the spot size and the intensity of the Ion Beam Induced Luminescence (IBIL), the scintillator is one of the most important parts of IPEM. In this study, we propose that the diamond containing a high concentration of Nitrogen Vacancy (NV) centers can be used as a scintillator with high spatial resolution. For both diamond and $Y_3Al_5O_{12}$:Ce (YAG:Ce) proposed by Branson et al.[1], the minimum spot size is a few micrometers. The IBIL intensity from diamond containing NV centers is 4 times higher than that from YAG:Ce. According to these results, we suggest that diamond containing NV centers is a rival candidate of YAG:Ce from the point of view of single ion detection with high spatial resolution.

[1] J. V. Branson et al., Nucl. Instr.And Meth. B 269 (2011) 2326

C-9 Focused ion beam fabrication of a diamond detector with buried graphitic electrodes

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In the present work we report a microfabrication technique for the realization of three-dimensional particle detector in single crystal diamond with the employment of focused MeV ions.

The interaction between matter and energetic ions induces lattice defects that are located mainly at the end of ion range. These distorted regions convert into a graphitic phase after high temperature thermal annealing. The use of implantation masks with graded thickness at the sub-micrometer scale allows the formation of conductive channels which are embedded into the insulating matrix at controllable depths. In particular, the modulation of the channels depth at their endpoints allows the surface contacting of the channel terminations with no need of further fabrication stages.

The obtained structures could be employed as electrodes in order to develop new geometry ionizing radiation detector.

C-10 Sharing of anomalous polarity pulses in a ion-beam-micromachined multi-electrode diamond detector

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Shockley-Ramo-Gunn theory [1] is a solid and well established tool for evaluating and modeling charge induction and transport mechanism in solid state detectors.

New results obtained in this framework allowed for the interpretation of charge sharing effects in multi-electrode devices. Among other effects, model led to the prediction of anomalous polarity charge induction pulses [2], under suitable geometrical and electrostatic configurations of the device under investigation.

A first validation of the model was performed against experimental data, by the Ion Beam Induced Charge analysis of a multi-electrode ion-beam-micromachined [3]detector grade CVD diamond sample with buried graphitic electrodes.

Charge collection efficiency maps were acquired at different voltage configurations, allowing for a comparison with predicted behavior and providing a satisfactory validation of the proposed model.

[1] E. Vittone et al., Nucl. Instr. and Meth. B 161-163 (1-4) (2000) 446

[2] J. Yorkston and A.C. Shotter, Nucl. Instr. and Meth.A 262 (1987) 353

[3] P. Olivero et al.,Nucl. Instr. and Meth. B 269 (2011) 2340

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