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Ion Beam Induced Charge analysis of diamond diodes

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ABSTRACT

Diamond based p-i-n light-emitting diodes, developed to electrically drive single-photon sources in the visible spectral region at room temperature, have the potential to play a key role in quantum based technologies. In order to gain more insight into the charge injection mechanism occurring in these diodes, we carried out an experiment aimed to investigate the electrostatics and the charge carrier transport by the Ion Beam Induced Charge (IBIC) technique, using 1 MeV He microbeam raster scanning of p-i-n structures fabricated in a high purity diamond substrate, using lithographic masking and P and B ion implantation doping.

Charge Collection Efficiency (CCE) maps obtained at low ion fluence, show that induced charge pulses arise only from the P-implanted region, whereas no IBIC signals arise from the B-implanted region. This result suggests the formation of a slightly p-type doped substrate, forming a n^+-p-p^+, rather than the expected p-i-n, structure.

However, for high fluence scans of small areas covering the intrinsic gap, CCE maps are more uniform and compatible with a p-i-n structure, suggesting the occurrence of a "priming effect", which saturates acceptor levels resulting in a decrease of the effective doping of the diamond substrate.

1. Introduction

One of the most interesting features of diamond diodes is electroluminescence induced by charge injection in recombination centers and, remarkably, in individual single nitrogen-vacancy (NV) centers located in the intrinsic region [1]. The possibility to develop diamond optoelectronic devices with stable, room-temperature, electrically driven single-photon sources is a key technology with a broad range of application ranging from quantum communication, computing and metrology [2]. The electrical control of the charge state of NV centers in diamond requires the control of the Fermi level in the diamond band-gap, which has been successfully achieved by incorporating the luminescent center in an intrinsic diamond layer sandwiched between graphitic/-graphitic electrodes [3] or in p-i-n structures with graphitic ohmic contacts [4–6]. However, for the optimization of these devices and their standardization in the perspective of their large scale production, an accurate and spatially resolved characterization of their electrostatic features is essential.

This analysis can be effectively carried out by the Ion Beam Induced Charge (IBIC) technique, which has been widely proven to be suitable to provide valuable information on the electrostatic and transport characteristics of semiconductor/insulator electronic devices [7,8]. Besides, it is of high interest in the field of quantum technology, for example, for its potential to accurately measure the ion strike location for single atom deterministic doping [9,10] in silicon and for the detection of single low energy ion (Si, 200 keV) in diamond for the optimization of the production yield of single color centers [11].

However, to our best knowledge, IBIC technique has not been so far applied to the electronic characterization of p-i-n diamond structures, in order to extract electric field profiles, and carrier diffusion/drift lengths as done for example in Si, GaAs, SiC junction or Schottky diodes [7,12].

In order to explore the potential of IBIC in this field, in this paper, we report on the first IBIC analysis of diamond-based p-i-n light-emitting diodes capable of single-photon emission in the visible spectral region at room temperature [4].

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2. Experimental

The p-i-n diamond diodes were fabricated on an electronic grade ultra-pure highly polished (100)-oriented single crystal CVD diamond film, 0.5 mm thick, using photolithographic masking and ion implantation doping. The p-type and n-type regions were realized by the implantation of 70 keV B ions with a fluence of $2 \cdot 10^{16}$ ions/cm^2 and 90 keV P ions with a fluence of 10^{16} ions/cm^2, respectively.

Fig. 1 summarizes the P and B implantation and the vacancy profiles evaluated by SRIM2013 simulations [13].

After B and P implantation, the sample was annealed at 1600 °C for 4 h in vacuum.

This annealing process had a double function: first to convert the highly damaged cap layers into graphite, with a vacancy density overcoming the graphitization threshold (assumed to be $V_G = 10^{22}$ vacancies/cm^3 [14]). Second, to recover the diamond lattice from implantation damage and activate the P and B dopants located below this graphitized conductive layer, where the vacancy concentration is lower than V_G. The conductive graphitic cap layers act as ohmic contact to the buried doped regions and allow direct bonding to be performed without additional metallization [4].

The sample was finally mounted on a ceramic PCB and two diodes were connected to the PCB gold pads by Al wires (20 μm) soldered on the top graphitic layers. The back side of the sample had no electrical contacts. The gaps (namely i-gaps) between the P- and B- doped regions of the two diodes under study, namely B3 and C4, were 7 and 9 μm, respectively. Fig. 2 shows optical images of the sample and of one of the diodes with the electrical connections. The bias voltage was applied on the n$^+$ electrode.

IBIC characterization was carried out at the LIPSION nanoprobe laboratory of the University of Leipzig [15], using 1 MeV He ion beams (ion current ≈ 0.1 fA) focused down to 1 μm spot size. The electronic energy loss profile, which corresponds to the electron/-hole generation profile, induced by 1 MeV He ion in diamond extends to 1.8 μm in depth.

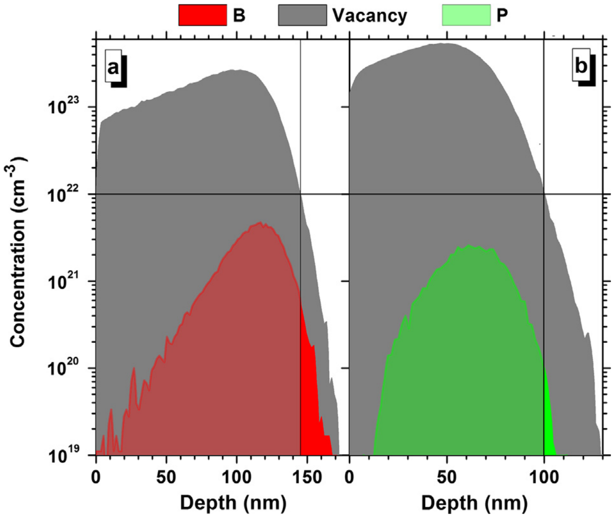

Fig. 1. a) Vacancy and implanted B profiles (70 keV, fluence = $2 \cdot 10^{16}$ cm^{-2}); b) vacancy and implanted P profiles (90 keV, fluence = 10^{16} cm^{-2}). The horizontal line indicates the graphitization threshold V_G. Regions on the left side of the vertical lines are relevant to highly damaged layers, with vacancy densities higher than V_G, which convert to graphite following the annealing process. On the right side of the vertical lines, the vacancy density is lower than V_G and the annealing process promotes both the recovery of the diamond lattice and the activation of dopants, providing p- and n-type buried layers (bright red and green regions for B and P doping, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

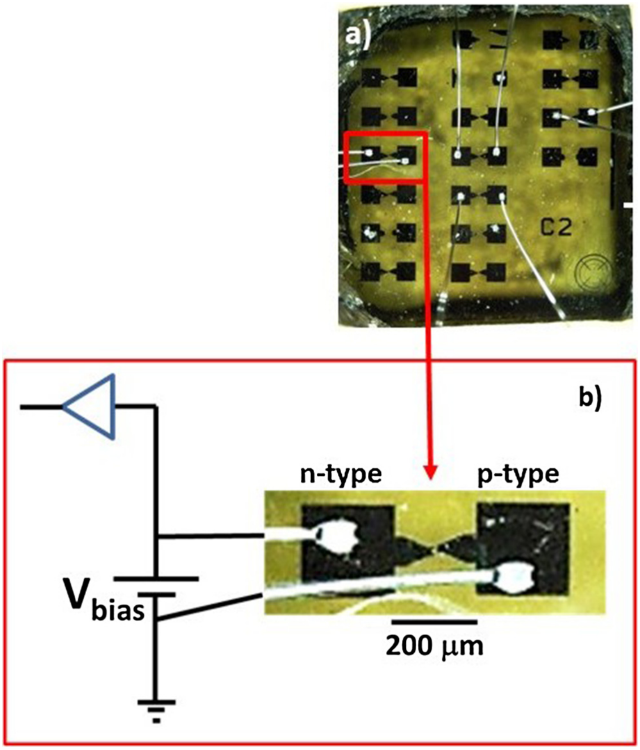

Fig. 2. a) Optical images of the diamond sample with the p-n junction diodes, c) optical image in transmittance of one diode with the scheme of the electronic connections.

The electronic chain was composed by an Amptek 250 charge sensitive pre-amplifier, a Canberra 2025 shaping amplifier (shaping time: 1 μs) and pulse heights were digitized by a Canberra 8701 ADC [16].

A Hamamatsu S1223-01 pin diode was used as the reference detector for Charge Collection Efficiency (CCE) calibration (assuming 100% CCE). The analysis of the 1 MeV He IBIC spectrum provides a spectral resolution of about 5 keV in Si; the noise threshold was set to channel 35, corresponding to 6300 electrons (≈23 keV in silicon). The CCE of diamond, was calculated assuming an electron/hole pair generation energy of 13 eV [17].

IBIC maps (typically 256 × 256 pixels) were acquired by scanning the ion micro-beam over the sample surface, and recording the charge pulse heights as function of the beam position. The ADC and beam scanning were controlled by the MicroDAS data acquisition system [18] working in "clock triggering mode" with dwell times of 500 μs and 1000 μs in each pixel, depending on measurement.

All the measurements were carried out in dark conditions [19] and at room temperature.

3. Results and discussion

Fig. 3 shows an IBIC map of a 720 × 720 μm^2 scan including the whole p-n structure. The "shadows" of the bonding and Al wires make easy the correlation between this map and the diode photograph shown in Fig. 2b. It is apparent that only the phosphorous implanted region is visible, whereas the charge induced when 1 MeV He ions probe the boron implanted region is null, or is below the electronic threshold (it should be noted that the B-doped region remained invisible in measurements with reversed polarity of the shaping amplifier). This result was unexpected,

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