Characterisation of SiC by IBIC and other IBA techniques

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Abstract

Several new technological applications of silicon carbide have attracted significant attention in recent years. As a wide gap semiconductor it has the capability to be used as a room temperature radiation detector. For most applications, material properties like homogeneity of charge transport, presence of defects, resistance to radiation damage, influence of light impurities (such as hydrogen) are of prime importance. Two different kinds of samples, crystalline (4H–SiC) and thin, amorphous (a-Si1−xCx:H) films, were studied using ion beam techniques. In the case of SiC single crystal radiation detectors, Li and proton beams with a wide range of energies were used to probe the charge collection efficiency at different device depths using the ion beam induced charge technique. Thin, amorphous and microcrystalline Si1−xCx:H films with a different stoichiometry and different degrees of structural ordering were examined using RBS and ERDA. © 2002 Published by Elsevier Science B.V.

1. Introduction

Silicon carbide is a very hard material, known for many years as “carborundum”, and used as an abrasive. It is the only group IV–IV naturally stable semiconductor, which can be used in devices which operate under severe conditions such as high power/high temperature, or in a high radiation environment. Among the many forms of crystallisations (different polytypes) only some are technologically important [1]. Electronic devices based on the 4H- and 6H–SiC polytypes presently exhibit the most promise due to the availability and quality of single crystal wafers.

Substantially higher carrier mobility makes 4H–SiC the polytype of choice for the production of radiation detectors [2,3]. With a band gap of 3.2 eV and high resistance, SiC is among the best semiconductor detectors suitable for operation at room and elevated temperatures. Typical commercially available 4H–SiC single crystal detector material was characterised using the ion beam induced charge (IBIC) technique in a nuclear microprobe. Frontal IBIC [4–6] using 7Li ions and protons, which have a range between 2.5 and 25 µm in SiC, was used to probe non-destructively the homogeneity of charge collection.

Apart from the evident applications of single crystals in electronics, amorphous SiC thin films are also interesting. Due to their optical, electronic and mechanical properties, a-SiC films are used in solar cell production, as a light emitting diodes,
phototransistors, and hard coatings [7–9]. Since these properties critically depend on the composition and structural ordering [10], establishing of reliable characterisation methods is very important.

The thin film a-Si\(_{1-x}\)C\(_x\):H (0.9 > x > 0.2) samples studied here have a typical thickness less than 1 \(\mu\)m, and were deposited by a magnetron sputtering process. Ion beam analysis (RBS and ERDA) was used for layer characterisation (thickness, Si/C ratio and H content) [11,12].

2. IBIC analysis of 4H–SiC radiation detectors

The thickness of the depletion layer, carrier drift and/or diffusion length, homogeneity of charge collection efficiency (CCE) and distribution of electrically active defects, as well as the sensitivity to radiation damage are the main parameters of radiation detectors that can be evaluated by IBIC. Depletion layer thickness and diffusion length were successfully measured in Si diodes by lateral IBIC as shown previously [13], but in the case of the available 4H–SiC samples this geometry could not be applied without incurring sample damage. Therefore a series of ion energies had to be used in a frontal geometry IBIC experiment in order to extract some of the information needed.

The Schottky diodes were fabricated on 4H–SiC epitaxial wafers purchased from CREE Research. The active layer thickness was 30 \(\mu\)m and the nominal net doping concentration of the active layer was \((N_d - N_a) = 2.2 \times 10^{15} \text{ cm}^{-3}\). The Schottky contact was circular and has been formed on the surface of the epitaxial layer by deposition of 100 nm of gold. Details on the geometry and on detector fabrication are given in [14]. Reverse bias voltages of up to 40 V were used with a leakage currents of less than 10 pA.

2.1. SiC detector performance

In these diodes, a rather thin (less than 5 \(\mu\)m thick) depletion layer was expected. This assumption was confirmed by initial IBIC measurements performed using \(^7\)Li ions of 2 MeV energy and a range in SiC of just 3.1 \(\mu\)m. With a simple change of bias, the saturation of CCE to a value of 100\% was obtained at reverse bias voltages above 20 V.

A series of IBIC measurements were performed using protons of energy 0.7–1.7 MeV in steps of 0.2 MeV. For the assumed SiC density of 3.2 g/cm\(^3\), proton ranges extended from 6 to 24 \(\mu\)m as evaluated by the SRIM code.

The measured sample was always kept at the same position for the whole range of incident ion energies. The microprobe set-up with narrow collimator and object slits of openings below 100 \(\mu\)m, resulted in very small divergence microbeam. This enabled a simple change of beam energy with only approximate adjustment of quadrupole currents, neglecting hysteresis. Due to the large scanning sizes and pixel size of more than 10 \(\mu\)m, image quality was not significantly reduced. However, measurement of the quadrupole magnetic field for more precise focusing adjustments at different ion energies is needed to obtain a high-resolution microbeam at smaller scan sizes.

Using a fixed reverse bias in the series of different proton energy measurements, different pulse height spectra were obtained. In order to minimise the contribution of areal inhomogeneity in the SiC sample response, a region (200 \(\times\) 200 \(\mu\)m\(^2\)) with the most homogeneous response was scanned. If the measured spectra are normalised to the ion energy, assuming 100\% CCE for 2 MeV \(^7\)Li IBIC spectrum, subsequent efficiency spectra are obtained, as presented in Fig. 1. It can be observed that efficiency is gradually decreasing with energy (Fig. 2(a)). Reduction of energy and therefore ion range, results in more and more energy deposited in the depletion layer where fast charge drift and total charge collection occurs. In such circumstances it can be expected that energy resolution (defined as the FWHM of the spectra divided by the relevant peak centroid) is decreasing with ion energy. Experimental results shown in Fig. 2(b) confirm this assumption.

2.2. Measurements of diffusion length

The diffusion length for minority carriers in silicon has been recently measured by IBIC in both
In frontal IBIC ions of range $R$ penetrate through the Schottky contact first into the depletion layer ($0 < x < x_d$) and then into the diffusion region ($x > x_d$). As given previously by Breese [15] and Vittone et al. [5], the efficiency of charge collection $\eta$ can be expressed by the following expression:

$$\eta = \frac{1}{N_{n.p}^{x_d}} \int_0^{x_d} G(x) \, dx$$

$$+ \frac{1}{N_{n.p}^{x_d}} \int_{x_d}^R G(x) \exp \left(-\frac{(x - x_d)}{L_p}\right) \, dx.$$  \hspace{1cm} (1)

$N_{n.p}$ is the total number of charge pairs created in the material, i.e. the ratio between the total ion energy and charge pair creation energy $e$. $G(x)$ is the depth profile of charge pairs created along the ion path, i.e. the electronic stopping power of ions divided by $e$. The first term in Eq. (1) represents the charge collected from the depletion region where fast charge carriers drift under the influence of electric field. Assuming the drift time much shorter then the carrier lifetime, the charge collection efficiency is supposed to be 100%. The second term of Eq. (1) represents the charge collected from the diffusion region. This term is obtained by integrating in time the net diffusion current of holes that arrive at the interface at depth $x_d$, considering an integration time (amplifier shaping time) much longer then the carrier lifetime. The depletion depth $x_d$, the diffusion length $L_p$ and the normalisation constant $N_p$ can be evaluated by solving a system of integral equations (1) where $\eta$ is given by the centroid position of the spectra shown in Fig. 1 and $G(x)$ and $R$ are given by SRIM simulation.

From the total of 6 IBIC measurements we obtained values for $x_d = 4.51 \pm 0.45 \mu m$ and $L_p = 8.41 \pm 0.17 \mu m$. Higher errors were obtained for the values of depletion layer thickness due to the slow change of efficiency at the $x_d$ depth.

### 2.3. Imaging of CCE inhomogeneities

IBIC images obtained using different ion energies include also information about the 3D distribution of CCE. This in fact reflects the presence of defects throughout the whole volume studied. However, in the depletion region where carriers drift very fast in the presence of electric field, re-
regions with increased defect density are much more difficult to visualise than the same regions in the diffusion region.

Therefore, more pronounced inhomogeneities are visible in IBIC images with higher proton energies where most of the ion energy loss occurs deeper in the diffusion region. Brighter spots visible in the 1.7 MeV image (Fig. 3) resemble defects known as micropipes. These are in fact hollow core dislocations frequently observed in SiC and having strong influence on the electrical properties of devices. Other bright regions that are visible in all images present either contact damage, or shallow radiation damage intentionally produced by 2 MeV Li ions (range in SiC 3.1 μm), prior to the proton IBIC measurements.

3. RBS and ERDA analysis of a-Si$_{1-x}$C$_x$:H thin films

Contrary to crystalline SiC samples where composition should be well defined, thin films of hydrogenated amorphous SiC films (a-Si$_{1-x}$C$_x$:H) exhibit different degrees of structural ordering and therefore their stoichiometry has to be determined by suitable techniques. In addition to the determination of different bonds in samples by IR spectroscopy (for hetero-polar bonds) and Raman spectroscopy (homo-polar bonds), ion beam scattering techniques (ERDA and RBS) can be used for determination of the total Si, C and H concentrations and their depth profile. In our attempt to establish a routine nuclear microprobe technique for determination of 3D distributions of these elements, a new detection system positioned in a forward angle was constructed. This system is based on micro-channel plate detection of secondary electron emission from a thin carbon foil, through which scattered and recoiled ions are transmitted to the energy detector [17]. As is seen in Fig. 4, where a broad beam was used to record spectrum of forward scattered and recoil particles, suitable detection limits for all significant elements in a-Si$_{1-x}$C$_x$:H can be obtained using a carbon ion beam. A carbon beam was used due to the relatively high currents that can be obtained by sputter ion source for the injection into the accelerator.
and nuclear microprobe. 9 MeV 12C ions were used with the particle detector positioned at a 45° angle. A typical experimental spectrum, accompanied by a SIMNRA [18] simulation indicating H and C contribution, in a 0.3 μm thick sample, are presented in Fig. 4.

4. Conclusions

In the development of radiation detectors based on silicon carbide, we showed that nuclear microprobe technique IBIC is an important tool in quantitative (depletion layer thickness and diffusion length) and qualitative (spatial distribution of defects in material and contact imperfections) characterisation of prototype detectors. From these measurements, the contribution of various parameters which influence the overall efficiency and energy resolution of the final device can be estimated. Furthermore, other IBA techniques were also successfully applied to the characterisation of amorphous and microcrystalline silicon carbide films, which do not have a well-defined stoichiometry as do monocrystalline samples. Results of ERDA and RBS of elemental analysis are complementary to FTIR and Raman spectroscopy that gave only results of particular bonds in thin film.

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References

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