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Development of diagnostic method for deep levels in semiconductors using charge induced by heavy ion microbeams

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ABSTRACT

In order to study defects that create deep energy levels in semiconductors which act as carrier traps, Charge Transient Spectroscopy using heavy ion microbeams (HIQTS) was developed at JAEA Takasaki. The HIQTS system was connected with the heavy ion microbeam line of the 3 MV Tandem accelerator. Using the HIQTS system, deep levels in 4H-SiC Schottky barrier diodes irradiated with 3 MeV-protons were studied. As a result, a HIQTS peak with an activation energy of 0.73 eV was observed. In addition, local damage in 6H-SiC pn diodes partially irradiated with 12 MeV-O ion microbeams was studied using HIQTS. With increasing 12 MeV-O ion fluence, charge collection efficiency in locally damaged areas decreased and HIQTS signals increased.

1. Introduction

Deep-level defects which act as carrier traps are created in semiconductors during crystal growth, device fabrication and also operation under radiation conditions. It is well-known that materials and device characteristics are degraded by such deep-level defects [1–3]. Therefore, it is important to characterize deep levels in semiconductors. Deep Level Transient Spectroscopy (DLTS) is a well-known and widely-used technique to investigate deep levels [4–6]. However, conventional DLTS does not well work for samples with high resistivity. For deep level investigation in samples with high resistivity, Current DLTS (IDLTS) in which transient current is measured instead of capacitance [7], and Photo Induced Current Transient Spectroscopy (PICTS) was proposed [8]. However, PICTS has a disadvantage that semi-transparent contacts must be fabricated since the method requires injection of laser light into the sample to generate carriers (electrons/holes). To overcome this issue, DLTS using charge generated by ion incidence (Scanning Ion Deep Level Transient Spectroscopy: SIDLTS) was proposed [9–11]. Laird et al. at the University of Melbourne studied defects in Au/Si Schottky barrier diodes (SBDs) with micrometer spatial resolution using SIDLTS with 2.1 MeV-He ion microbeams. Since DLTS including IDLTS cannot investigate defects in semiconductors with micrometer spatial resolution, this is an advantage of SIDLTS. Recently, we developed a deep level evaluation system based on Charge Transient Spectroscopy using alpha particles from 241Am source (Alpha Particle Charge Transient Spectroscopy: APQTS) and studied the effects of deep-level defects generated in 6H Silicon Carbide (SiC) pn diodes by electron irradiation on their characteristics as particle detectors [12]. As a result, it was revealed that the degraded charge collection efficiency (CCE) for 6H-SiC pn diodes due to irradiation by 1 MeV electrons at a fluence of $1 \times 10^{15}/\mathrm{cm}^2$ was recovered by annealing at 250 °C for 30 min, and the recovery occurred due to annealing of a deep-level center labeled as X by APQTS (Ei by DLTS). APQTS is thought to be a powerful tool to study defects in wide bandgap semiconductors such as SiC. However, since alpha particles from radio isotopes are used in our APQTS measurement system, no spatial resolution is expected. On the other hand, a heavy ion microbeam line has been developed at JAEA Takasaki [13–15]. Therefore, defect study with micrometer spatial resolution can be achieved if we apply the microbeam line

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to the QTS measurement system. In addition, since heavy ions create dense electron–hole pairs in a relatively narrow range, the depth distribution of defects can be investigated using microbeams with different energies and different ion species. Thus, by controlling the parameters of heavy ion microbeams, three-dimensional information about the defects can be obtained. We refer to this technique as Heavy Ion Induced Charge Transient Spectroscopy, HIQTS. (Actually, since the principle of HIQTS is the same as that of SIDLTS, we can say that HIQTS is one of the SIDLTS techniques. However, we call this technique "HIQTS" to distinguish it from APQTS that we developed [12].)

In this study, we report the development of a HIQTS system at JAEA Takasaki.

2. Experimental

2.1. Heavy Ion Charge Transient Spectroscopy (HIQTS)

Fig. 1 shows the schematic of Charge Transient Spectroscopy measurement system using heavy ions installed at JAEA Takasaki. The HIQTS measurement system is connected with the heavy ion microbeam line of the 3 MeV Tandem accelerator [13–15]. Charge induced in a sample by incident ions (probe ions) is amplified using a charge sensitive preamplifier (ORTEC 142A). Then, the charge signals (cumulative charge as a function of time) are recorded using a digital storage oscilloscope (Agilent Technologies DSO-X2024A). During cumulative charge measurements, the reverse bias is applied to a sample, and ion microbeams are scanned in order to avoid damage creation in a sample by ions used as probe. Since a liquid nitrogen (Lq. N_2) circulation unit with heaters is embedded in the sample stage in the irradiation chamber, charge induced in a sample by incident ions can be measured at various temperatures. Both cumulative charge measurement and temperature control systems are controlled using in-house software based on Lab VIEW. The rate window method is used to analyze HIQTS signals in a similar manner as DLTS [4,5].

Next, the measurement principle of HIQTS is briefly explained. Figs. 2(a), (b) and (c) show the schematic band diagrams of an *n*-type SBD applied to a reverse bias with charge generated by ion incidence, with charge trapped by deep levels and with charge released from deep levels, respectively. When a heavy ion penetrates in a SBD, dense charges (electron–hole pairs) are generated in the SBD as shown in Fig. 2(a). Since a reverse bias is applied to the SBD, induced electrons/holes are immediately swept away from the depletion region to *n*-type substrate/metal electrode due to the electric field. If carrier trap centers (deep levels) exist in the SBD, a portion of the carriers are captured by the deep levels (Fig. 2(b)). Especially, it seems that carrier trap centers are prone to capture carriers induced by ions during the space charge screening state (transient disappearance of the electric field by the generation of electron–hole pairs with high density) [10]. Electrons/holes captured by trap centers slowly escape to the conduction/valence band by thermal energy, and electrons/holes flow to *n*-type substrate/metal electrode under the reverse bias condition (Fig. 2(c)). Therefore, we can obtain the information on carrier trap centers by measuring charge slowly collected from a SBD at various temperatures. Since dense electron–hole pairs can be created in any semiconductor by ion irradiation, we can apply HIQTS techniques even to highly resistive semiconductors, including intrinsic material. This is a significant advantage of HIQTS compared to conventional DLTS. In addition, when microbeams are used as the probe for HIQTS measurements, we can investigate carrier traps with micrometer spatial resolution. However, it should be also mentioned that we cannot distinguish majority or minority carrier traps from HIQTS signals because both electrons and holes are created by ion irradiation and both carriers are captured by carrier trap centers.

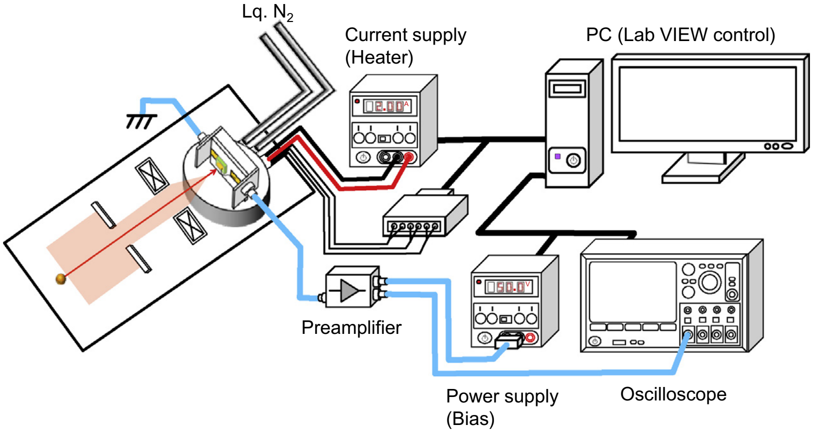

Fig. 1. Schematic of HIQTS measurement system installed at JAEA Takasaki.

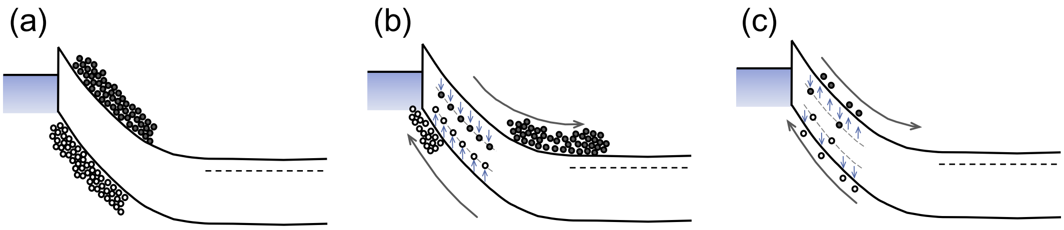

Fig. 2. Schematic band diagrams of an *n*-type SBD applied to a reverse bias (a) with charge generated by ion incidence, (b) with charge trapped by deep levels and (c) with charge released from deep levels.