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ABSTRACT

Minority hole diffusion length and lifetime were measured in independent experiments by electron beam-induced current and time-resolved cathodoluminescence in Si-doped β-Ga_2O_3 Schottky rectifiers irradiated with 18 MeV alpha particles and 10 MeV protons. Both diffusion length and lifetime exhibited a decrease with increasing temperature. The non-equilibrium minority hole mobility was calculated from the independently measured diffusion length and lifetime, indicating that the so-called hole self-trapping is most likely irrelevant in the 77–295 K temperature range.

β-Ga_2O_3 is a group-III semiconductor oxide with a bandgap of ~4.7 eV. Over the past decade, it is becoming increasingly attractive due to its robustness and applications in high-power electronics, optoelectronic devices in the ultraviolet (UV), true solar-blind UV detection, and transparent conductive substrate.[1–6] Over the last decade, minority carrier transport properties, such as diffusion length, lifetime, and mobility in n-type β-Ga_2O_3, were extensively studied.[7–18] The realization of p-type conductivity has been a challenge until recently because of the self-trapped nature of holes, leading to low mobility (1×10^{-6} cm^2 V^{-1} s^{-1}).[19] Contrary to this prediction, the relatively high experimental values for hole diffusion length in n-type β-Ga_2O_3 (50–600 nm) indicated that holes were indeed mobile at room temperature and their self-trapped nature is likely relevant for temperatures below 120 K.[9,20,21]

A limited number of techniques is available to directly determine the mobility of excess non-equilibrium carriers. Recently, pump–probe spectroscopy and time-resolved photoluminescence techniques were used to measure the dynamics of self-trapped holes[22] and self-trapped excitons (STEs).[23] Moreover, lifetimes of ~200 ps for conduction electrons resulted from fast light pulse excitation.[24] Lee *et al.*[9] measured diffusion length (L) and excess carrier lifetime (τ) independently in Si-doped β-Ga_2O_3 Schottky rectifiers subjected to 1.5 MeV electron irradiation using Electron Beam-Induced Current (EBIC) and Time-Resolved Cathodoluminescence (TRCL). At room temperature, L and τ were found to be 330 nm and 215 ps, respectively, resulting in a surprisingly high non-equilibrium hole mobility (μ) of ~200 cm^2 V^{-1} s^{-1}. These values were found to reduce significantly with exposure to electron irradiation with varying fluences.

Experimental measurements of L, τ, and μ for excess non-equilibrium holes in n-type β-Ga_2O_3 exposed to various radiation sources, and their temperature dependence, are desirable. In this study,

the focus is on measurement of minority transport properties, namely L and τ, in Si-doped β-Ga_2O_3 Schottky rectifiers, exposed to proton and alpha-particle radiation in 77–295 K temperature range.

Sn-doped (n^+, carrier concentration $\sim 2.2 \times 10^{18}\,cm^{-3}$) β-Ga_2O_3 substrate (orientation [001]) grown by Edge-Defined Film-Fed Growth (EFG) technique was used for deposition of epitaxial β-Ga_2O_3 layer with Halide Vapor Phase Epitaxy (HVPE). The 20 μm thick epitaxial layer was doped with Si (electron concentration $\sim 3.6 \times 10^{16}\,cm^{-3}$) and was planarized to a thickness of 10 μm by chemical/mechanical polishing. Schottky contacts were fabricated by Ni/Au deposition (20 nm/80 nm) on the epitaxial layer, followed by photolithography and liftoff. Finally, Ohmic contacts on the backside of the substrate were made by blanket deposition of Ti/Au (20 nm/80 nm). The calculated maximum electric field for the Schottky contacts was 0.1 MV/cm for 0 V bias used in the measurements[25] and 1.22 eV barrier height.[26] A schematic diagram of the rectifiers is shown in Fig. 1(a). The samples were divided in groups with the first as control. The second group was exposed to 10 MeV proton radiation generated by MC-50 cyclotron at Korea Institute of Radiological and Medical Science with a fluence of $5 \times 10^{14}\,cm^{-2}$. The proton beam completely irradiated the epitaxial β-Ga_2O_3 layer with a range of 330 μm in the material. Similarly, the third group of samples was exposed to 18 MeV alpha particle radiation with a fluence of $1 \times 10^{12}\,cm^{-2}$ and penetration depth of 80 μm. The beam current of the cyclotron was 100 nA in both cases. Furthermore, the carrier removal rates of the proton- and alpha particle-irradiated samples were measured to be $237\,cm^{-1}$ and $406\,cm^{-1}$, respectively. Additional irradiation and fabrication details can be found elsewhere.[27,28]

L and τ were measured *in situ* in an Attolight Chronos Scanning Electron Microscope (SEM) fitted with a temperature-controlled stage (CryoVAC TIC 500) using EBIC line-scan technique (planar configuration) and TRCL, respectively. The beam energy was kept fixed at 10 keV for both techniques with electron range (R_e) of 0.4 μm in the material.[29] The ratio $R_e/L < 4$ ensured L not to be limited by EBIC resolution.[30] The EBIC signal was amplified with a Stanford Research Systems low-noise amplifier (SR570) and recorded with a Keithley DMM 2000 digital multimeter connected to a PC with data acquisition software. Figure 1(b) shows an EBIC line-scan acquired at 77 K. The cathodoluminescence (CL) signal was collected by a mirror assembly directly above the sample. This assembly is spatially coupled to a streak camera (Optronis Optoscope with resolution ~2 ps) through Horiba iHR 320 spectrometer. In the time-resolved mode of operation, electron pulses with width ~8 ps were generated by focusing a femtosecond laser (Onefive Genki HP-03, 80 MHz), synchronized with the streak camera, on the electron gun tip.

L was extracted from the EBIC line-scan according to:[31,32]

$$I_{EBIC}(x) = I_0 x^{\alpha} \exp\left(-\frac{x}{L}\right). \quad (1)$$

Here I_0 is a constant; x is the distance from the junction to the electron beam; L is the minority hole diffusion length; and α is a constant related to the surface recombination rate. Furthermore, $\alpha = -0.5$, indicative of a low influence of surface recombination rate, was chosen for analysis. A fit to EBIC signal acquired at 77 K with $x^{\alpha}\exp(-x/L)$ is shown in Fig. 1(b) (inset). The measured value of L at room temperature was found to be 106 nm for the control structure, close to 110 nm, gathered from an independent study.[33] All measured values of L are in agreement with literature, with L ranging from 50 nm[33] to 600 nm.[34] A strong correlation between the beam probe current and L was discovered (with a different location for every measurement), indicating the sensitivity of the material to electron beam exposure. The dependence of L on extended duration electron beam exposure in β-Ga_2O_3 and other wideband gap semiconductors was reported in earlier studies, where the final value of L depends on the net charge density deposited in the region of the measurement.[35–42] The rate of L enhancement with the net deposited charge in alpha- and proton-irradiated structures was observed to be lower compared to the control sample.[36] In this study, a new location is chosen for every EBIC line-scan in conjunction with a small beam current of ~8 pA, to minimize the charge injection effect.

The temperature dependence of L for control, alpha-, and proton-irradiated diodes is shown in Fig. 2. Activation energy for the temperature dependence of L can be extracted from[39,43]

$$L(T) = L_0 \exp\left(\frac{\Delta E_{A,T}}{2kT}\right). \quad (2)$$

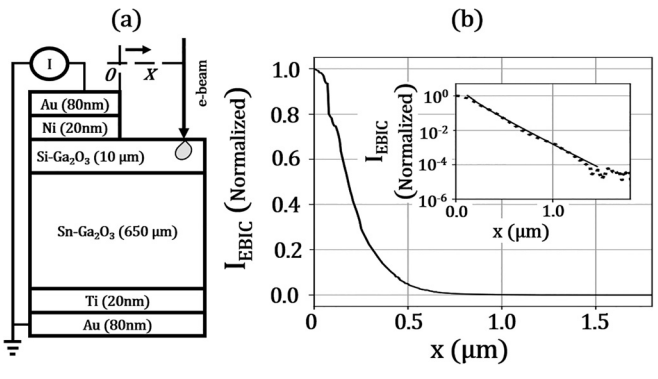

FIG. 1. (a) A schematic diagram of the sample structure and experimental setup. (b) An example of the acquired EBIC line-scan from the control structure at 77 K. Inset shows the raw data with $x^{0.5}\exp(-x/L)$ fit for extraction of the diffusion length.

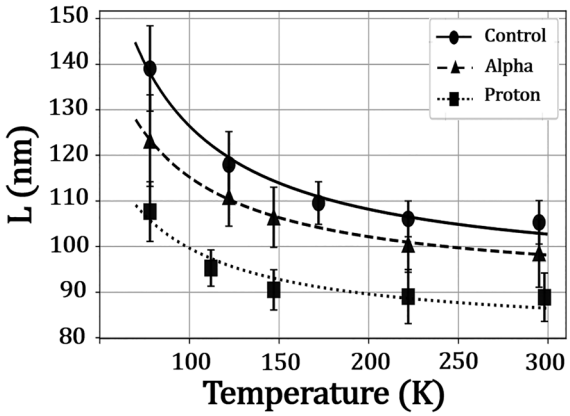

FIG. 2. Temperature dependence of diffusion length for control, alpha-, and proton-irradiated structures.

Here, L_0 is a constant; $\Delta E_{A,T}$ is thermal activation energy; k is the Boltzmann constant; and T is the temperature in Kelvin. $\Delta E_{A,T}$ for control, alpha-, and proton-irradiated structures was calculated as 5.4, 4.1, and 3.7 meV, indicating a weak temperature dependence. In earlier studies on GaN,[35,42,44] Ga_2O_3,[7,36,37] and ZnO,[39,40] $\Delta E_{A,T}$ was associated with trap levels in the forbidden gap, but the currently found values are clearly smaller than the activation energies of any known trap levels in the bandgap. A probable origin of the decreased activation energy is the increased carrier recombination with rise in the temperature. A direct factor contributing to the low activation energy is the relatively small value of L compared to other reported values,[8,9,28] likely due to the charge injection effect due to the magnitude of the electron beam current in use.

A TRCL streak of the characteristic ultraviolet luminescence (UVL) centered around 380 nm in β-Ga_2O_3 is shown in Fig. 3 (continuous CL spectra are given in Ref. 9). The TRCL streak from Fig. 3 obeys a single exponential decay described by[45]

$$A(t) = A_0 \exp(-t/\tau) + C. \quad (3)$$

Here, A_0 is the initial integrated CL intensity; t is the delay after excitation; τ is the decay constant; and C is a constant associated with luminescence persisting longer than the excitation period of 12.5 ns (80 MHz). Equation (3) is consistent with the observation of fast and slow decay constants by Binet and Gourier[18] and other studies.[46–48] In this study, for the measurement on a picosecond timescale, C is approximated by a constant for the extraction of lifetime. τ is obtained by fitting the streak signal with Eq. (3).[9,18,49]

τ decreased from 572 ps, 523 ps, and 464 ps at 77 K to 168 ps, 159 ps, and 154 ps at 295 K for control, alpha-, and proton-irradiated samples, respectively (Fig. 4). The measured value of τ at room temperature for the control structure is comparable to the previously reported TRCL data of 215 ps.[9] The irradiated structures sustain additional point defects due to radiation damage and, therefore, exhibit reduction in L as well as τ.[21,27,28,50,51] The values of L and τ were largest for the control structure, followed by alpha- and finally proton-irradiated structures. This observation could be attributed to the fluence of proton-irradiation being over two orders of magnitude larger than alpha-irradiation.

UVL in Si-doped β-Ga_2O_3 is associated with the self-trapped excitons (STEs) and recombination involving Si_{Ga} donors and V_{Ga},

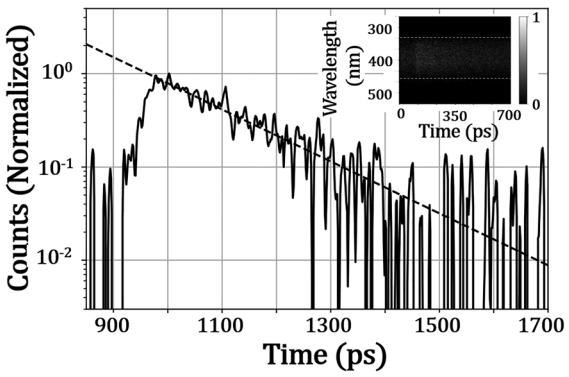

FIG. 3. A TRCL streak acquired at 295 K for control structure and the associated raw streak image (inset).

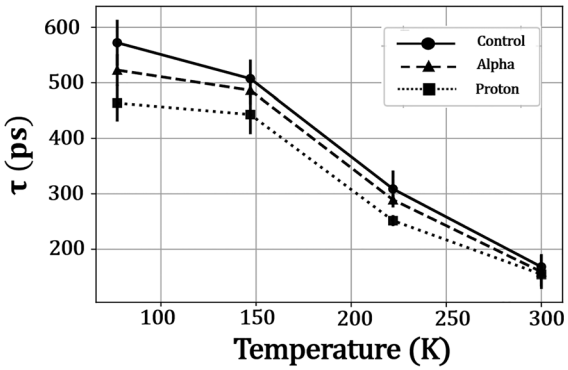

FIG. 4. Dependence of excess carrier lifetime on temperature for control, alpha-, and proton-irradiated structures.

V_O–V_{Ga} complexes.[48,52] Onuma *et al.*[53] discovered that around 150 K, where most STEs have thermally disassociated,[20] non-radiative recombination centers (NRCs) play a significant role in the carrier recombination. This was revealed in Si-doped β-Ga_2O_3 by CL thermal quenching with increasing temperature. A recent study by Huynh *et al.*[54] of UVL in β-Ga_2O_3 identified the presence of Fe^{3+} impurity (~0.6 eV below conduction band minimum) that acts as an efficient non-radiative recombination center, inhibiting the carriers from participation in other recombination channels. Saturation of Fe^{3+} centers, facilitating non-radiative recombination, was studied by observing the magnitude of the CL signal while varying the electron beam current. At temperatures above 150 K, ionization of Si-donors, emission of weakly bound electrons from STEs (increases the number of available recombination centers),[20,49] and participation of NRCs are likely responsible for reduction in excess carrier lifetime with increasing temperature in Fig. 4.

Under low injection conditions (beam current < 1 pA in TRCL mode[55]) the excess carrier lifetime from a mono-exponential TRCL decay is assumed to be equal to the minority carrier lifetime (hole lifetime, in this case).[45,56] The minority carrier diffusion length and lifetime are related by the Einstein relation

$$L = \sqrt{D\tau} = \sqrt{\mu k_B T \tau / q}. \quad (4)$$

Here, D is the diffusivity and q is the electron charge. Equation (4) contains L and τ measured from independent experiments and can be used to calculate minority carrier mobility (μ). Figure 5 shows the variation of μ with temperature for control, alpha-, and proton-irradiated samples. It is worth mentioning that τ, used in Eq. (4) for mobility calculations, is obtained under short (~8 ps) electron excitation pulses. Therefore, the calculated mobility is transient in nature and is different from Hall mobility varying with temperature as $T^{\pm 3/2}$. While the room temperature μ in the control sample calculated in Ref. 9 with a similar approach was in excess of ~200 $cm^2\ V^{-1}\ s^{-1}$ for $L = 330$ nm and $\tau = 215$ ps, in this study, μ at room temperature was found as ~25 $cm^2\ V^{-1}\ s^{-1}$ for $L = 106$ nm and $\tau = 168$ ps. This shows that the magnitude of L has a significant impact on the calculated transient mobility of non-equilibrium minority holes. The latter mobility is two-to-three orders of magnitude higher than the measured equilibrium majority hole mobility of 0.2 $cm^2\ V^{-1}\ s^{-1}$ in p-type β-Ga_2O_3.[57]

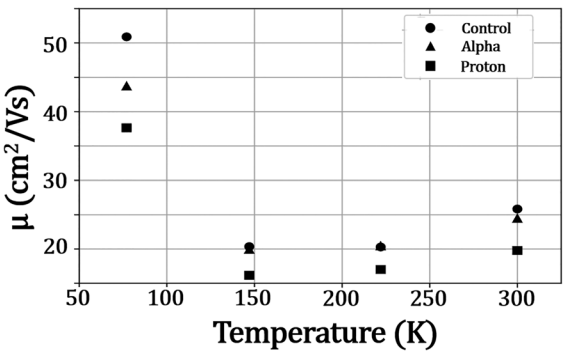

FIG. 5. Mobility calculated with Eq. (4) from independently measured L and τ for control, alpha- and proton-irradiated structures. The mobility value at T = 147 K for control sample was calculated based on the fitted value of L temperature dependence.

In this study, the activation energies of $\leq$5.5 meV, pertaining to decrease in L with increasing temperature, likely originate from the increase in the carrier recombination rate. This is confirmed by a simultaneous reduction in the lifetime. L measured in this study is not impacted by charge injection effects and is, therefore, lower compared to the previously reported values.[7,9] Alpha- and proton-irradiation introduced additional recombination centers that resulted in a reduction of L and τ. Further, the activation energy extracted from the temperature dependence of L, decreased for the irradiated structures, thereby reducing the thermal barrier for the carrier recombination.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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