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1.5 MeV electron irradiation damage in β-Ga_2O_3 vertical rectifiers

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Vertical rectifiers fabricated on epi Ga_2O_3 on bulk β-Ga_2O_3 were subject to 1.5 MeV electron irradiation at fluences from 1.79×10^{15} to 1.43×10^{16} cm^{-2} at a fixed beam current of 10^{-3} A. The electron irradiation caused a reduction in carrier concentration in the epi Ga_2O_3, with a carrier removal rate of 4.9 cm^{-1}. The 2 kT region of the forward current–voltage characteristics increased due to electron-induced damage, with an increase in diode ideality factor of ~8% at the highest fluence and a more than 2 order of magnitude increase in on-state resistance. There was a significant reduction in reverse bias current, which scaled with electron fluence. The on/off ratio at −10 V reverse bias voltage was severely degraded by electron irradiation, decreasing from ~10^7 in the reference diodes to ~2×10^4 for the 1.43×10^{16} cm^{-2} fluence. The reverse recovery characteristics showed little change even at the highest fluence, with values in the range of 21–25 ns for all rectifiers. © *2017 American Vacuum Society*. [http://dx.doi.org/10.1116/1.4983377]

I. INTRODUCTION

β-Ga_2O_3 is likely to be very radiation hard,[1–3] based on its bond strength, but there is much basic information on the effects of radiation on charge collection, stoichiometric disturbances, defect creation, role of hydrogen, phase stability, and the scaling of these effects at small volumes that is missing. There is a need to measure the effects of total dose proton, electron, gamma ray, and neutron fluxes on Ga_2O_3, which has exceptionally high breakdown fields and great promise for high power, high temperature electronics. Monoclinic β-phase Ga_2O_3 has outstanding potential for power electronics[4–19] with a large direct bandgap of ~4.6 eV and the commercial availability of high quality, large diameter bulk crystals and epitaxial layers with a range of controllable n-type doping levels.[12]

Given the potential applications for Ga_2O_3 power electronics and photoconductors, they will commonly be subject to fluxes of high energy protons and electrons if used in low earth orbit satellites, as well as neutrons or gamma rays if used in radiation-hard electronics for nuclear or military systems. Each of these forms of radiation produces different types of damage. In addition, primary defects may recombine, form complexes with each other, with dopants and with extended defects; at high energies, the energy of the primary recoils becomes so high that they produce collision cascades and form heavily disordered regions with a very high defect density in the core. In general, proton and electron irradiation in wide bandgap semiconductors produces simple point defects in a semiconductor lattice,[20,21] while neutron irradiation creates extended defects called Gossick zones, which are heavily disordered core regions surrounded by a space charge region with strong band bending. The response to gamma irradiation is often quite complicated. Compton electrons induced from γ-radiation create electron–hole pairs, thus changing occupancy of traps. For proton and electron damage, the device degradation scales with dose and is correlated with the nuclear or nonionizing energy loss component of the ions traversing the active regions of the device which creates lattice displacements. Similar comments apply to neutron-induced damage, but the carrier removal rates for neutron irradiation are much lower than for protons.

There have been few published reports of radiation damage studies in β-Ga_2O_3. Our group reported on the effect of 5 MeV proton damage on photoconductivity in the material.[22] In this paper, we discuss the effect of 1.5 MeV electron irradiation on unterminated vertical β-Ga_2O_3 Schottky rectifiers. The carrier removal rate is found to be ~4.9 cm^{-1}, and the forward and reverse diode characteristics are strongly degraded only above doses of 1.79×10^{15} cm^{-3}.

II. EXPERIMENT

The starting samples were bulk β-phase Ga_2O_3 single crystal wafers (~650 μm thick) with (001) surface orientation (Tamura Corporation, Japan) grown by the edge-defined film-fed growth method. Hall effect measurements showed the Sn-doped samples had carrier concentration of 3.6×10^{18} cm^{-3}.[22] Epitaxial layers (initially ~20 μm thick) of lightly Si-doped n-type Ga_2O_3 (~2×10^{16} cm^{-3}) were grown on these substrates by hydride vapor phase epitaxy at Novel Crystal Technology. After growth, the epi surface was subjected to chemical mechanical polishing to remove pits. The final epi

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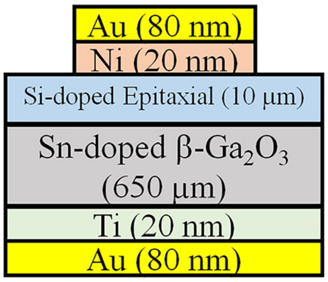

FIG. 1. (Color online) Schematic of vertical Ni/Au Schottky diode on Ga_2O_3 epilayer on a conducting β-Ga_2O_3 substrate.

layer thickness was ~10 μm. The x-ray diffraction full width at half maximum of the (402) peak was ~10 arc sec, and the dislocation density from etch pit observation was of the order of $10^3\,cm^{-2}$.

Diodes were fabricated by depositing a full area back Ohmic contacts of Ti/Au (20 nm/80 nm) by E-beam evaporation. Ohmic behavior was achieved without the need for dry etching. The front sides were patterned by lift-off of E-beam deposited Schottky contacts Ni/Au (20 nm/80 nm) on the epitaxial layers.[22] The diameter of these contacts were 105–510 μm. Figure 1 shows a schematic of the rectifier layer structure. The barrier height extracted from forward current characteristics was 1.05 eV. We did not observe any significant dependence of the electron irradiation results on diode size. In most cases, a diameter of 210 μm is used unless otherwise stated. Current–voltage (I–V) characteristics were recorded in air at 25 °C on an Agilent 4145B parameter analyzer or a Tektronix 370A curve tracer. For these moderately doped layers, the dominant current transport process in Schottky contacts is thermionic emission. The samples were irradiated in the electron-beam accelerator facility at the Korea Atomic Energy Research Institute. The beam energy was 1.5 MeV, and beam current was fixed at 1 mA. Three different fluences were used, namely, 1.79×10^{15}, 3.57×10^{15}, or $1.43 \times 10^{16}\,cm^{-2}$.

III. RESULTS AND DISCUSSION

Figure 2 shows the change in forward I–V characteristics of the rectifiers for the lowest and highest doses. The 2 kT current in the low voltage region increased due to the introduction of electron irradiation damage while the diode turn-on voltage shifted. We swept the I–V with different voltage directions, and there was no obvious hysteresis and thus the shift in turn-on voltage could be caused by the positively charged traps created by electron irradiation.[23] The loss of carriers is reflected in the increased series resistance obvious at higher voltages.

The reverse bias I–V characteristics showed the effects of carrier removal by introduction of electron traps. Figure 3 shows the I–Vs before and after the three different electron fluences. Note the strong reduction in reverse current with electron fluence when plotted on a linear scale.

The introduction of trapping centers is also clear from the increase in diode ideality factor and on-state resistance with

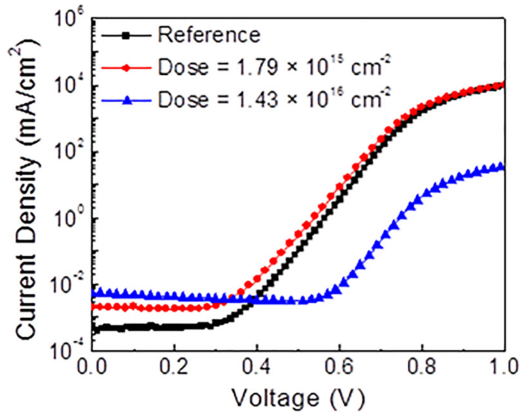

FIG. 2. (Color online) Forward current density-voltage characteristics before and after electron irradiation with the fluence 1.79×10^{15} or $1.43 \times 10^{16}\,cm^{-2}$.

increasing electron fluence, as shown in Fig. 4. The ideality factor of the unirradiated control rectifiers was 1.07, consistent with thermionic emission being the dominant current transport mechanism,[24–28] and an increase in this with electron irradiation is due to the introduction of generation-recombination centers. If the latter dominates the current transport, the ideality factor will be 2.[27,28] Similarly, the on-state resistance is given by[27]

$$R_{ON} = (W_D)/e\mu_n N_D,$$

where W_D is the depletion layer thickness, e is the electronic charge, μ_n is the electron mobility, and N_D is the background n-type doping level of the Ga_2O_3 epitaxial layer. If the effective carrier concentration in the epitaxial layer is decreased by the introduction of electron traps, then R_{ON} will increase.[29–31] The on-state resistance in the unirradiated diodes was 6 $m\Omega\,cm^{-2}$, and this increased by more than 2 orders of magnitude at the highest electron fluence.

Figure 5(a) shows the $1/C^{-2}$-V plots for the rectifiers after electron irradiation at the three different fluences and (b) the carrier concentration in the epitaxial Ga_2O_3 layer extracted from these plots, as a function of electron fluence. From this

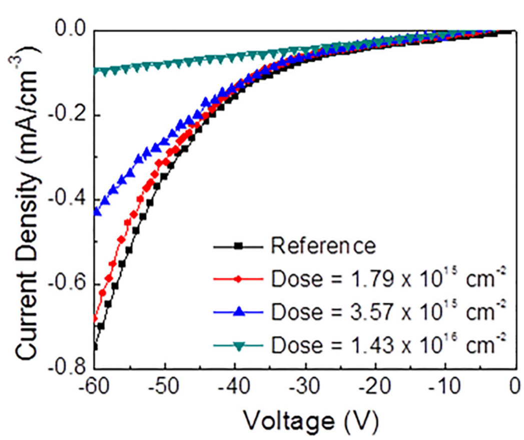

FIG. 3. (Color online) Reverse current density-voltage characteristics of Ga_2O_3 rectifiers before and after electron irradiation at three different fluences.

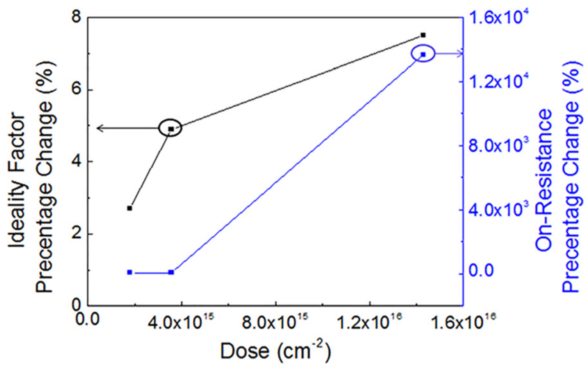

FIG. 4. (Color online) On-state resistance and diode ideality factor as a function of 1.5 MeV electron fluence.

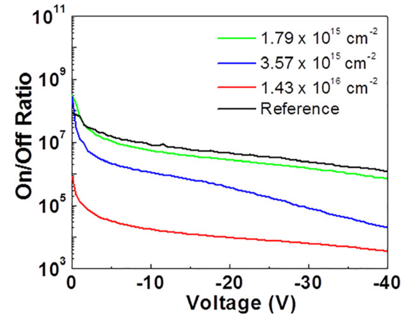

FIG. 6. (Color online) On/off ratio as a function of reverse bias voltage for rectifiers before and after electron irradiation at three different fluences.

data, we were able to calculate the carrier removal loss as 4.9 cm^{-1} at the lower doses where we can be sure that the loss is still linear with dose. Sometimes it is not clear in the literature that carrier removal rates are being calculated at high doses where the trap concentration is already so high that new traps are not contributing to carrier loss.[20,21] This carrier removal rate is comparable to that reported for electron irrdation of n-type GaN.[20]

Figure 6 shows the rectifier on/off ratio when switching from +1 V forward bias to the reverse voltages shown on the x-axis. The unirradiated rectifiers showed on/off ratios of $\sim 10^7$ for switching to -10 V, and this was degraded by the electron irradiation. This is due to the rapid reduction of forward current as the carrier density is reduced by the irradiation-induced trap introduction. These results show how the operating characteristics of the rectifiers are degraded by exposure to high electron fluences.

We also measured the reverse recovery characteristics when switching from +5 to -5 V and found recovery times of order 26 ns, as shown in Fig. 7. These hardly change with electron fluence across the whole dose range investigated, showing that this parameter is not sensitive to damage introduction since the minority carrier lifetime (which controls the carrier storage time in the intrinsic layer) is already short in Ga_2O_3.[8,12]

IV. SUMMARY AND CONCLUSIONS

Vertical geometry Ga_2O_3 rectifiers were irradiated with 1.5 MeV electrons to fluences up to 1.43×10^{16} cm^{-2}. There is a reduction in carrier density in the drift region of the rectifiers with a carrier removal rate of 4.9 cm^{-1}. This leads to a shift in forward turn-on voltage, a reduction in reverse current density, and increases in both diode ideality factor and on-state resistance of the rectifiers. The on/off ratio is also degraded, but the reverse recovery characteristics show little change, even at the highest fluences. The Ga_2O_3 shows comparable radiation hardness to GaN.

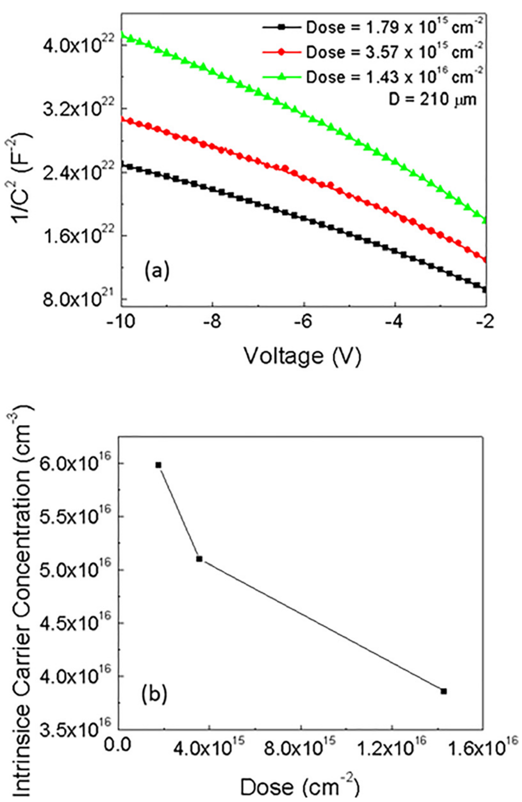

FIG. 5. (Color online) (a) $1/C^{-2}$-V plots for rectifiers after electron irradiation at the three different fluences and (b) carrier concentration in the epitaxial Ga_2O_3 layer as a function of electron fluence.

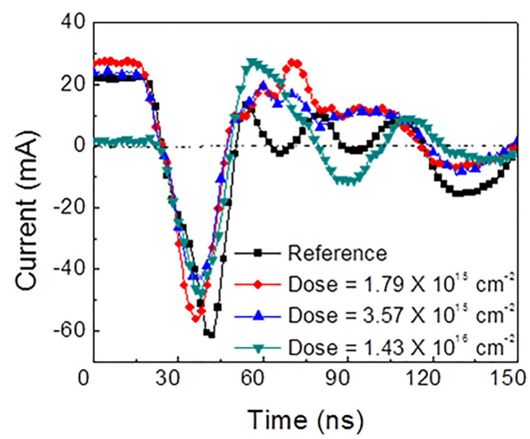

FIG. 7. (Color online) Reverse recovery characteristics of rectifiers before and after electron irradiation at three different fluences.

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