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Aperture-Limited Conduction from Acceptor Diffusion in Current Aperture Vertical β-Ga_2O_3 MOSFETs

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Abstract

Nitrogen ion implantation was employed to form the current blocking layer (CBL) in current aperture vertical β-Ga_2O_3 MOSFETs. A nonlinear turn-on behavior exhibited in the drain characteristics of these devices was attributed to an electron barrier in the aperture due to diffusion of charged acceptor defects from the CBL into the aperture. The effective migration energy of the defect species was 3.1 eV, consistent with diffusion of gallium vacancies. These results reveal the critical impact of point-defect diffusion in the performance of ion-implanted Ga_2O_3 devices.

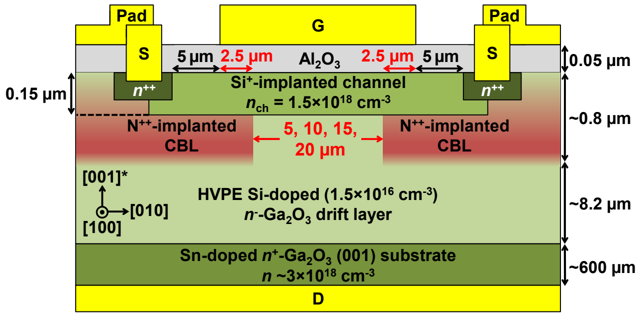

Fig. 1. Cross-sectional schematic of current aperture vertical Ga_2O_3 MOSFET.

1. Introduction

Beta-phase gallium oxide (β-Ga_2O_3, referred to hereinafter as Ga_2O_3) possesses a wide bandgap (4.5–4.9 eV) and a large critical field strength that are attractive for high-voltage power devices [1]. High-quality melt-grown native substrates offer a cost-competitive platform to this technology. Capitalizing on highly manufacturable ion-implantation technologies for donor (silicon) [2] and deep acceptor (nitrogen) [3] doping of Ga_2O_3, we have demonstrated vertical Ga_2O_3 MOSFETs in which silicon-ion (Si^+) implanted top n^{++} source contacts are electrically isolated from the bottom drain contact by a nitrogen-ion (N^{++}) implanted current blocking layer (CBL) except at an aperture bounded by CBLs through which the drain current (I_D) is conducted [4]. As it is imperative that the aperture size (L_{ap}) be optimized to prevent current choke while maintaining a small specific on-resistance ($R_{ON,sp}$), this work studied the effect of L_{ap} on the on-state characteristics of current aperture vertical Ga_2O_3 MOSFETs, the results of which were suggestive of diffusion of acceptors into the aperture.

2. Device Fabrication

Figure 1 shows a cross-sectional schematic of the vertical Ga_2O_3 MOSFET. Devices were fabricated on a 9-µm-thick Si-doped (1.5×10^{16} cm^{-3}) n^--Ga_2O_3 drift layer grown by halide vapor phase epitaxy (HVPE) on an n^+-Ga_2O_3 (001) substrate. N^{++} was implanted into Ga_2O_3 at 480 keV with a dose of 4×10^{13} cm^{-2}, leading to a peak nitrogen concentration of 1.5×10^{18} cm^{-3} at 0.5–0.6 µm below the surface. Thermal annealing of the N^{++}-implanted Ga_2O_3 was carried out at 1100°C for 30 min in N_2 to recover implantation damage and activate nitrogen as an acceptor. Subsequent Si^+ implantations at multiple energies and doses defined the electron channel (1.5×10^{18} cm^{-3}, 0.15-µm-thick box profile) and n^{++} source contact layers (5×10^{19} cm^{-3}, 0.1-µm-thick box profile) that were activated at 950°C and 800°C, respectively, for 30 min in N_2, whereby full activation of n_{ch} was achieved. A 50-nm-thick Al_2O_3 gate dielectric was then formed by plasma-enhanced atomic layer deposition and patterned to open windows over the n^{++} source regions by BCl_3 reactive ion etching. A Ti/Au metal stack, annealed at 470°C for 1 min in N_2, was used for the top source and bottom drain ohmic electrodes. The gate electrode was formed by Ti/Pt/Au. Source probing pads, which consisted of Ti/Au, were deposited on the Al_2O_3 for low pad leakage. The MOSFETs had a nominal gate length of 2.5 µm, a source width of 2×200 µm, an aperture width of 200 µm, and variable L_{ap} of 5, 10, 15, and 20 µm.

3. Results and Discussion

DC output characteristics of the vertical MOSFET with L_{ap} = 20 µm are shown in Fig. 2(a). At a gate voltage (V_G) of +5 V, the device had an $R_{ON,sp}$ of 17.2 mΩ·cm^2 and an maximum I_D 0.62 kA/cm^2, where both values were normalized to the area of the Si channel implant. Drain curves of all four MOSFETs at V_G = +5 V are shown in Fig. 2(b). The device with an L_{ap} of 20 µm displayed linear I_D turn-on with drain voltage (V_D), whereas those with L_{ap} of 5 and 10 µm displayed Schottky characteristics that indicated the presence of an electron barrier in the current path due presumably to aperture

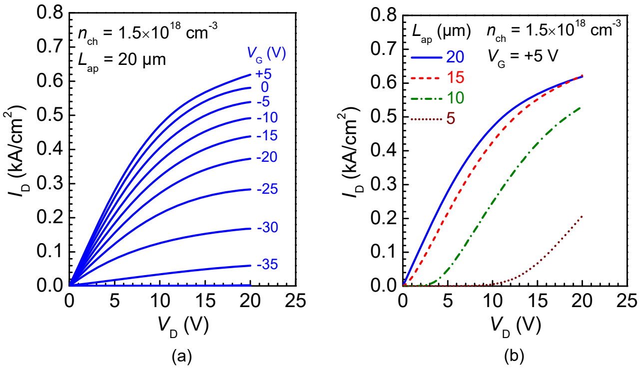

Fig. 2. (a) Family of DC I_D–V_D curves for MOSFET with L_{ap} = 20 µm. (b) L_{ap} dependence of drain characteristics at V_G = +5 V.

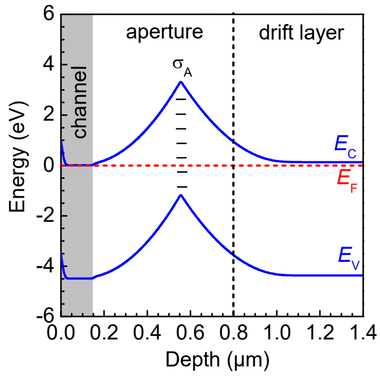

Fig. 3. Planar-doped barrier diode model for analyzing V_{ON} vs. σ_A at the center of the aperture.

choke, the onset of which took place at an L_{ap} of 15 µm. Assuming a built-in voltage equal to the bandgap of Ga_2O_3 (4.5 eV) at the aperture–CBL junction, a depletion region of about 0.6 µm thus formed at each of the two lateral junctions would not have pinched even the smallest 5-µm aperture, given that the simulated lateral implant straggle was only about 0.5 µm.

The turn-on voltage (V_{ON}) displayed by the devices could be explained by a presence of acceptors in the aperture and modeled by a planar-doped barrier diode (Fig. 3), wherein an electron barrier was created by a negative acceptor sheet charge (σ_A) at a depth corresponding to the projected range of nitrogen. A diode with an σ_A of 1.8×10^{12} cm^{-2} required 15 V to turn on—the situation for an L_{ap} of 5 µm. These acceptors had most likely originated from lateral diffusion of native point defects from the ion-implanted CBLs during the post-implantation annealing process as migration of nitrogen should be negligible [3, 5]. The process of diffusion created a gradient in σ_A across the aperture, which translated to a gradient in barrier height such that turn-on would be initiated at the center of the aperture where the least resistive path existed. Since the acceptors only had a finite diffusion length, the minimum barrier height to overcome and hence V_{ON} decreased as L_{ap} increased.

Insights into the identity of the acceptor defect could be obtained by estimating the defect migration barrier. According to transition state theory [6], the rate of defect migration is given by $\Gamma = \Gamma_0\exp(-E_A/k_BT)$, where E_A is the migration barrier, k_B is the Boltzmann constant, T is the temperature, and Γ_0 is the jump frequency that corresponds to a typical phonon frequency of 10^{13} Hz in Ga_2O_3. Assuming a hopping distance of 1 Å, a migration length of 7.5 µm during nitrogen implant activation—distance the acceptor species would need to diffuse in order to close the aperture—corresponded to an E_A of 3.1 eV. This barrier was consistent with diffusion of gallium vacancies (V_{Ga}) [7], a well-known native deep-acceptor defect in Ga_2O_3 with low formation energies in *n*-type materials [8, 9]. However, it should be noted that the extracted E_A was an effective value and did not unequivocally identify a specific acceptor defect. In addition to uncertainties involved in assigning the migration path that led to macroscopic diffusion, multiple thermally activated processes that impacted diffusion could be embodied in E_A, e.g. a formation energy to account for defect generation, or a detrapping energy if diffusion was trap-limited due to defect capture at donor dopants or other defect sites. Advanced defect spectroscopy will yield informative results for future investigations into this subject.

4. Conclusion

The performance of current aperture vertical Ga_2O_3 MOSFETs was found to be impacted by diffusion of charged acceptor defects from N^{++}-implanted CBLs into the aperture. The resultant barrier to electron transport necessitated larger L_{ap} to restore aperture conductivity at the expense of $R_{ON,sp}$. On the basis of the extracted defect migration energy, V_{Ga} was deduced to be the most plausible acceptor species but further work is needed for a more complete understanding. This work highlights the role of point-defect diffusion in the performance of ion-implanted Ga_2O_3 devices.

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