Molecular beam epitaxy of undoped β-Ga_2O_3 (010) for Si-ion-implanted field effect transistors

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The success of wide-bandgap Ga_2O_3 for future power devices depends critically on high quality epitaxial layers with controllable doping. Molecular beam epitaxy (MBE) of Sn-doped β-Ga_2O_3 (010) has been restricted to relatively low growth temperatures (T_g) of about 560°C with a narrow window to prevent Sn surface segregation while preserving high crystal quality [1]. The advent of Si ion (Si^+) implantation for *n*-type doping lifts the growth constraint imposed by *in-situ* Sn doping [2]. This work demonstrates that T_g can appreciably influence the resistivity of unintentionally-doped (UID) and the conductivity of Si^+-implanted Ga_2O_3, thereby highlighting new considerations as well as tradeoffs for achieving device epilayers with optimal structural and electrical properties.

1.2-μm thick UID Ga_2O_3 epilayers were grown by ozone MBE at 560°C, 590°C, 620°C, 650°C, 680°C, and 710°C, respectively, on Fe-doped insulating β-Ga_2O_3 (010) substrates. Ohmic contacts and 0.3-μm thick conductive layers typical of Ga_2O_3 transistor channels were formed by Si^+ implantation doping at 3×10^{17} cm^{-3} and 5×10^{19} cm^{-3}, respectively. [001]-oriented transmission line model (TLM) structures, electrically isolated by UID material without mesa etching, were fabricated to extract the sheet and contact resistances. Inter-device leakage was characterized by isolation test structures consisting of 100-μm-wide conductive regions spaced 22 μm apart.

Consistent with prior observations, smooth UID Ga_2O_3 epilayers were obtained at $T_g \leq 650$°C whereas increased roughness due to step bunching was evident at higher T_g [1]. The leakage current through UID Ga_2O_3 measured on isolation test structures at 200-V bias showed up to seven-fold reduction by increasing T_g from 560°C to 650°C and beyond (Fig. 1). Secondary ion mass spectroscopy revealed that unintentional Si incorporation during MBE growth, which could be effectively suppressed at high T_g though showed no direct correlation with morphological evolution, was responsible for the high background conductivity. The channel sheet resistance ($R_{sh,channel}$) showed insignificant dependence on T_g with weak variations that likely tracked fluctuations in carrier mobility or background acceptor levels (Fig. 2). All $R_{sh,channel}$ values were consistent with highly efficient to full channel implant activation. On the other hand, abrupt decrease in the activation efficiency of the contact implant for the lowest T_g of 560°C as well as the step-bunched epilayers grown above 650°C led to associated degradation in metal-semiconductor contact resistance ($R_{c,M\text{-}S}$) and specific contact resistivity ($\rho_{c,M\text{-}S}$) (Fig. 3). The reasons for a T_g window for efficient contact implant activation remain to be investigated.

The above results suggest a T_g window of 620 – 650°C for smooth, resistive UID Ga_2O_3 epilayers and efficient Si^+ implant activation. Further electrical testing on transistors will establish and validate optimal conditions.

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[1] K. Sasaki, *et al.*, J. Cryst. Growth **392**, 30 (2014). [2] K. Sasaki *et al.*, Appl. Phys. Express **6**, 086502 (2013).

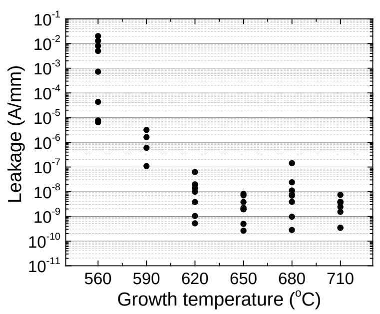

Fig. 1. Leakage current through UID Ga_2O_3 showed up to seven-fold reduction from T_g of 560°C to 650°C and beyond.

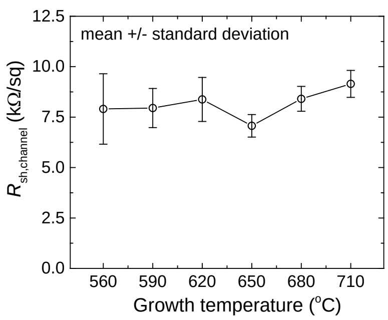

Fig. 2. $R_{sh,channel}$ showed insignificant variations with T_g.

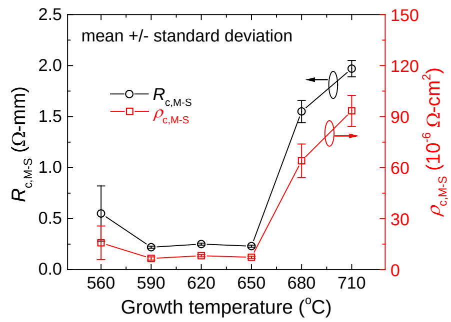

Fig. 3. Dependence of $R_{c,M\text{-}S}$ and $\rho_{c,M\text{-}S}$ on T_g showing degradation for materials grown at 560°C and above 650°C.