Delta Doping β-Ga_2O_3 Grown Via Plasma Assisted Molecular Beam Epitaxy Using Germanium

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Abstract

We utilized secondary ion mass spectroscopy (SIMS) and capacitance-voltage (CV) measurements to develop the capability to delta dope β-Ga_2O_3 films using Germanium via plasma-assisted molecular beam epitaxy (PAMBE). The background doping of Ge in the films was 2 orders of magnitude lower than what was observed in Si as measured via SIMS. Using a Ge cell temperature of 700 °C, a substrate temperature of 550 °C, a delta-doped structure that was capped with 50 nm of unintentionally doped β-Ga_2O_3 was grown and then measured by CV. The CV profile revealed a sharp peak at 58 nm into the sample with an integrated sheet concentration of 1×10^{13} cm^{-2} and a peak width of 12 nm at 10% of the maximum volume concentration.

INTRODUCTION

β-Ga_2O_3 has been of interest due to its large, predicted critical breakdown field (8 MV/cm) [1] and its ability to be grown from the melt for easy manufacturability. [2-4] With the availability of native substrates being prevalent, studying the growth and doping of β-Ga_2O_3 thin films has been of great interest. Early Si delta doping studies showed promise with a Si background of 1×10^{17} cm^{-2} with good sheet carrier concentrations of 1.2×10^{13} cm^{-2}. [5] However, silicon has been identified to leave a significant background when the cell is left closed but hot in the chamber, based on shutter design and MBE geometry, so these results are not consistent from system to system. [6]

Ge has been investigated in β-Ga_2O_3 growth previously via PAMBE [7] and more recently via metal-organic chemical vapor deposition (MOCVD). [8] MOSFETs have also been successfully fabricated using Ge-doped material from PAMBE. [9] With such success and investigation into further doping properties, Ge seems like a good candidate for delta doping applications where Si may fail due to the difficulties presented by its oxidation. In this work, we report our investigation into the challenges of Si doping and how Ge may be used to supplement the device designs that Si may not be able to properly accomplish.

EXPERIMENTAL

β-Ga_2O_3 films were all grown on Fe and Sn doped (010) oriented β-Ga_2O_3 substrates purchased from Novel Crystal Technology Inc. (NCT). Before insertion into the growth chamber, the substrates had a Ti/Pt metal stack deposited on the backside to allow for infrared absorption from the growth module's heater. The substrates were then diced into smaller 5×5 mm pieces to optimize the number of experiments that could be carried out on a single substrate. The substrate surfaces were cleaned by performing a standard clean of Acetone followed by Methanol which was followed by a final Isopropanol rinse after dicing. The substrates were loaded into Haynes 230 holders and baked in the introduction chamber at 200°C for 4 hours to boil off any water. After insertion into the growth module, the substrate surfaces are exposed to an oxygen plasma for 15 minutes prior to growth to perform a descum.

Growth was conducted in a Veeco GENXCEL molecular beam epitaxy (MBE) system, capable of accepting substrates up to 4 inches in diameter. β-Ga_2O_3 growth was performed with a standard dual heated Ga SUMO effusion cell operating at beam fluxes ranging from 4.0×10^{-8} torr to 4.0×10^{-7} torr. Ga source material was provided by United Material Corp. (UMC) at 99.99999% purity. Oxygen was provided by a radio frequency (RF) plasma source operating at powers ranging from 200 W - 300 W and oxygen flow rates between 1.0 and 2.0 sccm. n-type doping was achieved using standard dopant effusion cells of Si and Ge, with the source material also provided by UMC at 99.99999% purity. Growth temperatures were measured by thermocouple and ranged from 500°C to 650°C.

Secondary ion mass spectroscopy (SIMS) was performed by Evan's Analytical Group (EAG) to detect dopant concentrations in the material.

STUDY RESULTS

When growing β-Ga_2O_3 with the Si cell shutter closed and idling the Si cell at 900 °C prior to a delta doping attempt similar to the one presented in [5], the SIMS in Fig. 1 shows the background created by the Si cell is 2×10^{18} cm^{-3} and the

delta doping peak is only ~5 × 10^{18} cm^{-3}. This is due to the active oxidation of the Si cell in the chamber as discussed in [6]. This result indicates that achieving delta doping in a commercially available PAMBE system is not viable, and thus a new dopant of choice must be identified to achieve easy delta-doped structures.

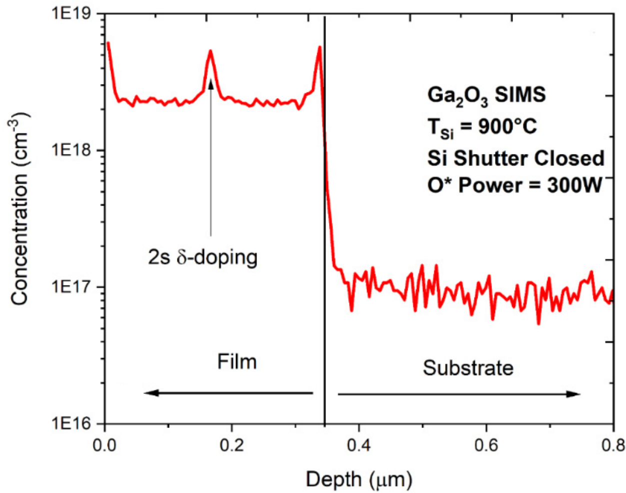

Figure 1: SIMS of a delta doping attempt with Si from [6]. The large background makes the delta doping peak rather unimpressive.

Based on experiments by Neal *et. al.* Ge acts as a shallow donor similar to Si in β-Ga_2O_3. [10] We proceeded to attempt doping with Ge based on previous studies. [7] Doping proved to be a challenge as many factors such as substrate temperature and site competition dominated dopant incorporation as shown in Fig.2 By slightly adjusting the Ga beam flux in the PAMBE system the doping concentration changed two orders of magnitude. Using 1 × 10^-7 torr as our Ga beam flux the Ge incorporation is 2 × 10^{17} cm^{-3} while reducing the beam flux to 6 × 10^{-8} torr results in incorporation on the order of 10^{19} cm^{-3}. Additionally, Fig 2. seems to suggest that by changing the Ge cell temperature (T_{Ge}) there is no major change in dopant incorporation, removing the possibility of doping as you would in traditional PAMBE systems. This causes instability in the doping profile from sample to sample, as some beam fluxes are preferential for particular electronic properties as opposed to others. Without the ability to control the incorporation by cell temperature, the growth of Ge-doped β-Ga_2O_3 films is significantly more difficult and unlikely.

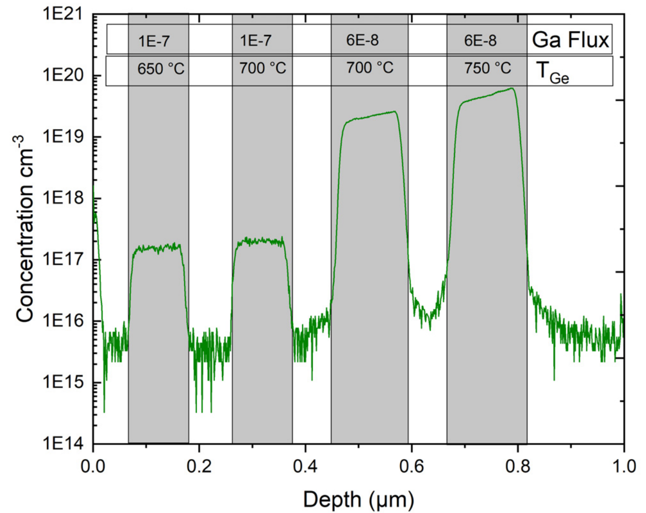

Figure 2: Ge SIMS stack with varying the temperature of the Ge cell and the Ga beam flux.

However, by comparing Fig.1 to Fig.2 one can see that the background of the Ge doping is significantly lower when doping with Ge as its oxide does not have the same effect on the doping profile as Si does as explained in [6]. Ge shows a background in the 10^{16} cm^{-3} range depending on the amount of Ge incorporated as opposed to the 2 × 10^{18} cm^{-3} seen in the Si films as discussed previously. This is a promising result that can allow for Ge to be used for delta doping as one only needs to incorporate a large dose of Ge for a short period of time to accomplish delta doping.

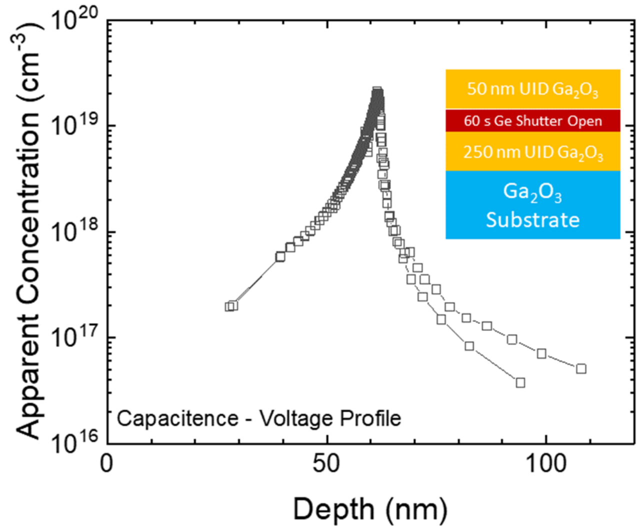

Figure 3: The CV profile of the Ge delta-doped structure and a diagram of the grown structure.

Based on this knowledge we attempted to characterize a Ge delta-doped sample. The epitaxial layer design is shown in Figure 3. To electrically isolate the Ge delta doping layer

from both the surface and the film-substrate interface, a 250 nm UID buffer layer was grown, followed by a 60 s delta doping layer which should be near ~1.5 nm based on our calibrations. The sample was capped with a 50 nm UID layer to isolate the delta doping layer from the sample surface. The substrate temperature was 550 °C while T_{Ge} was 700 °C. The sample was characterized by CV depth profiling and we compare the CV results of the Ge delta-doped film, seen in Fig. 3, to similar values identified in SIMS in our attempts with Si doping as seen in Fig. 1 in Table I.

TABLE I: Delta Doping Data Comparison

Dopant	**UID Background**	**Peak Concentration**	**Sheet Concentration**
Si	2.0×10^{18} cm^{-3}	5.0×10^{18} cm^{-3}	N/A
Ge	5.1×10^{16} cm^{-3}	2.1×10^{19} cm^{-3}	1.0×10^{13} cm^{-2}

The results show that the UID background has decreased 3 orders of magnitude from 2.0×10^{18} cm^{-3} to 5.1×10^{16} cm^{-3} when using Ge as shown in Table I. This result also allowed a proper sheet concentration calculation to be done revealing that the sheet concentration is 1.0×10^{13} cm^{-2} based on the integration of the CV depth profile in Fig. 3. The CV measurement also showed at 10% of the peak concentration the delta-doped peak was 12 nm wide. This observation is a large improvement with Ge compared to Si, and demonstrates that Ge can be used to properly delta dope β-Ga_2O_3.

CONCLUSIONS

Delta-doping β-Ga_2O_3 is difficult to achieve using Si. Ge has been shown to be difficult to control for uniform doping applications as it is sensitive to the Ga beam flux and can not be controlled via the Ge cell temperature as is done in PAMBE traditionally. However, we demonstrated the ability to use Ge for a delta-doped structure which yielded good electrical results. This ability to delta dope with an unmodified dopant cell is useful for others that are looking for an easily manufacturable solution to high quality β-Ga_2O_3 films with doping for device development. This reduces the need for tricks and lowers the bar of entry in β-Ga_2O_3 device development.

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ACRONYMS

PAMBE: Plasma-Assisted Molecular Beam Epitaxy
SIMS: Secondary Ion Mass Spectroscopy