Co-Implantation and Autocompensation in Close Contact Rapid Thermal Annealing of Si-Implanted GaAs:Cr

C. W. FARLEY, T. S. KIM and B. G. STREETMAN

The University of Texas at Austin
Microelectronics Research Center
Austin, Texas 78712

Close contact rapid thermal annealing of semi-insulating GaAs:Cr implanted with Si, Si + Al, and Si + P has been studied using variable temperature Hall effect measurements and low temperature (4.2K) photoluminescence (PL) spectroscopy. Isochronal (10 sec) and isothermal (1000 °C) anneals indicate that As is lost from the surface during close contact annealing at high anneal temperatures and long anneal times. Samples which were implanted with Si alone show maximum activation at an annealing temperature of 900 °C, above which activation efficiency decreases. Low temperature Hall and PL measurements indicate that this reduced activation is due to increasing autocompensation of Si donors by Si acceptors at higher anneal temperatures. However, co-implantation of column V elements can increase the activation of Si implants by reducing Si occupancy of As sites and increasing Si occupancy of Ga sites, and thereby offset the effects of As loss from the surface. For samples implanted with Si + P, activation increases continuously up to a maximum at an anneal temperature of 1050 °C, and both low temperature Hall and PL measurements indicate that autocompensation does not increase in this case as the anneal temperature increases. In contrast, samples implanted with Si + Al show very low activation and very high compensation at all anneal temperatures, as expected. The use of column V co-implants in conjunction with close contact RTA can produce excellent donor activation of Si implanted GaAs.

Key words: implantation, annealing, GaAs

INTRODUCTION

Rapid thermal annealing (RTA) has become an attractive alternative to traditional steady-state furnace annealing of ion implanted GaAs. Various methods of providing the power to rapidly heat the sample have been investigated, but the use of incoherent light sources appears to be the most promising. Regardless of the power source used, it is evident that the GaAs surface must be protected from decomposition at the anneal times and temperatures needed to produce good implant activation. In a rapid thermal annealing environment, protection can be provided by encapsulation, an As ambient, a combination of the two, or another GaAs wafer in close contact with the sample to be annealed. The close contact method is the simplest approach, but there is inevitably some As loss during annealing. The resulting stoichiometric imbalance can influence the electrical activation of implanted impurities, and even their migration during annealing.

The electrical activity of amphoteric dopants such as Si is particularly sensitive to stoichiometry and may be influenced by the use of co-implants of column III and V elements. Yuen et al. considered the effect of As co-implantation on the site selection of Si implanted into GaAs annealed using rapid thermal annealing at 1050 °C for 2 seconds. Photoluminescence spectra show a noticeable decrease in the Si acceptor peak for the As co-implanted sample. Also, Hall measurements show increased electrical activation in the co-implanted sample which are accompanied by a decrease in room temperature mobility. However, they did not conduct a systematic investigation into the effects of co-implantation on Si site selection. Krautle studied the effect of co-implantation on the electrical activation of several column IV impurities implanted into GaAs and annealed for 30 minutes in an H2/AsH3 ambient. Hall effect measurements show that for high dose (1014 to 1016 cm−2) Si implants, Ga co-implantation reduces Si activation and As co-implantation increases activation. Therefore it is useful to examine the compensation of Si implants and methods to reduce compensation in such annealing methods. In this study, we use variable temperature Hall effect measurements and 4.2K PL spectroscopy to examine Si autocompensation during close contact rapid thermal annealing and the control of these effects by co-implantation of column III and V elements along with Si to influence its donor or acceptor activity.

EXPERIMENTAL METHODS

The substrates used in this study were (100) Cr-doped semi-insulating (SI) LEC GaAs. Samples were prepared with a standard technique of degreasing using boiling trichlorethane, acetone, methanol, and DI rinse, followed by an oxide etch in (1:1) HCl:H2O and a final DI rinse and dry. The samples were then implanted with 150 keV 28Si ions to a fluence of 1

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Analysis of the mass spectra for the Si implant showed that the mass 28 beam contained less than 1% $^{28}\text{N}_2$. For the co-implanted samples, $1 \times 10^{14}$ cm$^{-2}$ fluences of $^{28}\text{Al}$ and $^{31}\text{P}$ were implanted at 140 keV and 160 keV, respectively. These energies were chosen to match the projected range of all the implants (1550 Å). Phosphorus was chosen instead of As as the column V co-implant because of its lighter mass, which reduces damage production. Aluminum was chosen instead of Ga for the same reason.

All anneals were performed in a forming gas atmosphere (10% H$_2$ in N$_2$) in an infrared lamp RTA system designed in our laboratory.$^{10}$ Prior to annealing, the furnace tube was purged for several minutes at room temperature with forming gas, after which the sample was heated to 300°C in 30 sec and held there for an additional 30 sec. This preheat cycle was used to improve the reproducibility of the temperature response of the RTA system. The sample was then heated to the anneal temperature as rapidly as possible (~100°C/sec) and held at that temperature for the chosen time. The tube was then flushed with a high flow rate of N$_2$ to rapidly cool the samples (~50°C/sec). All anneals were carried out with a GaAs "cap" in close contact with the GaAs sample to be annealed, as shown in Fig. 1. The temperature response of samples annealed using this configuration has been studied in detail.$^{11}$ Over the range of anneal times and temperatures used in these experiments, the temperature of the GaAs sample varied by no more than 10°C from the setpoint temperature measured in the Si susceptor. Excellent reproducibility of implant damage annealing and activation was determined from transport and PL measurements.

Variable temperature Hall effect measurements were performed using the van der Pauw method to determine sheet carrier concentrations and mobilities. Ohmic contacts to the implanted layer were made using a 10% Sn: 90% In alloy which was heated to 450°C for 30 sec in flowing forming gas. The presence of hydrogen in the atmosphere during alloying is necessary to produce stable and reproducible contacts. PL measurements were carried out at 4.2K using the 5145Å line of an Ar ion laser. It should be noted that the PL measurements were performed on the same samples that were characterized by variable temperature Hall effect measurements.

**RESULTS AND DISCUSSION**

1. **Hall Effect Measurements**

Figure 2 shows the room temperature sheet resistance of Si and Si + P implanted layers as a function of RTA temperature. The minimum sheet resistance of Si implants is reached at an anneal temperature of 900°C. As the RTA temperature increases further, the sheet resistance also increases, as reported by others.$^{1,4,6}$ This increase could result from mobility degradation due to physical decomposition of the sample, reduced Si concentration due to outdiffusion during annealing, increased compensation of Si donors by vacancies or vacancy-related complexes, or increased autocompensation of Si donors by Si acceptors. However, one cannot determine which mechanism is responsible for the increased sheet resistance from this data alone. Phosphorus co-implanted samples anneal quite differently in that the sheet resistance continues to decrease to a minimum at 1050°C. As for the Si case, the mechanism responsible for the rise in sheet resistance at higher RTA temperatures cannot be determined from room temperature sheet resistance measurements alone.

Figure 3 shows the percentage of donor activation of Si implants with and without P or Al co-implants, as determined from the sheet carrier concentration in room temperature Hall effect measurements. The activation efficiency of Si implanted samples decreases as the RTA temperature exceeds 900°C, whereas this decrease is not seen for P co-implanted samples until the anneal temperature exceeds 1050°C. One can conclude from these data that the fluctuations in sheet resistance seen in Fig. 2 are largely due to changes in sheet carrier concentration as the RTA temperature increases.