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MICROWAVE ANNEALING OF ION IMPLANTED 6H-SiC

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ABSTRACT

Microwave rapid thermal annealing has been utilized to remove the lattice damage caused by nitrogen (N) ion-implantation as well as to activate the dopant in 6H-SiC. Samples were annealed at temperatures as high as 1400 °C, for 10 min. Van der Pauw Hall measurements indicate an implant activation of 36%, which is similar to the value obtained for the conventional furnace annealing at 1600 °C. Good lattice quality restoration was observed in the Rutherford backscattering and photoluminescence spectra.

INTRODUCTION

In the past several years SiC has received a great deal of attention for its potential use in semiconductor device applications. SiC has certain qualities that could make it extremely attractive for use in high-temperature and high-power integrated circuits [1]. The SiC devices could be used up to temperatures as high as 700 °C provided that the packaging technology can withstand such an extreme environment. This material has the additional advantage of being chemically inert, which would allow the devices to be exposed to corrosive or similarly harsh environments without degradation. Another aspect of SiC, is that the electron saturation velocity is about three times higher than that of Si [1]. This would allow the device to operate at higher speeds, as far as switching logic is concerned. The higher speed of the device would also permit circuits to operate in a higher frequency range (i.e, microwave range) as compared to Si. SiC has three main polytypes which are currently being used for discrete and integrated circuit fabrication. They consist of 3C (cubic), 4H, and 6H (hexagonal). In this study we have used only 6H-SiC.

In fabricating planar SiC devices, it is necessary to use ion implantation as the vehicle for doping, using various impurities. Thermal diffusion techniques would be highly impractical since the diffusion coefficients of impurities in SiC are extremely low thereby requiring temperatures as high as 1800 °C for long periods of time [1]. The sample would decompose at such a high temperature due to the thermal evaporation of Si. Ion implantation provides the user with the capability of selective area doping without the need of subjecting the material to extreme temperatures. However, during the process of implantation the crystal lattice of the SiC is damaged as the ions penetrate it. The damaged material must then be subjected to heating in order to restore the crystal lattice to its original structure. This process also has the effect of electrically activating the implants [2]. At present, the implanted SiC is annealed in ceramic processing furnaces at temperatures as high as 1650 °C [3]. Because the conventional annealing process can take several hours due to slow ramp up and ramp down times, the possibility of using microwaves for rapid thermal processing has been explored. This helps to prevent redistribution of impurity atoms during annealing [4].

Microwave energy can provide a fast and efficient method to high temperature anneal SiC, with the proper insulating material. Microwave energy can be directed and tuned, which will cause the material to heat up locally at an accelerated rate [5-8]. Rise rates of 300 °C/ min have been achieved, compared to 10 °C/min, in the conventional annealing techniques. This process has the possibility of being scaled up so as to anneal arrays of wafers in the same short time period, (unlike halogen lamp RTP) which is one of the requirements for commercial application. The intention is to investigate this new technology by annealing 6H-SiC samples which have been implanted with nitrogen. Electrical and lattice quality tests were performed on these samples in order to compare them with conventional annealing.

EXPERIMENT

The microwave annealing experiments were carried out in a TE_{103} single mode cavity with a variable power source of 1 kW. In order to achieve maximum energy efficiency and heat the samples to a high temperature in a short ramp time, critical tuning and coupling was achieved and maintained during the entire annealing process by adjusting the position of a moving plunger and the size of an adjustable iris. A directional coupler was used to monitor the reflected power. The temperature of the samples was measured by a two-color pyrometer and controlled by manually varying the input power.

The samples used for the annealing tests were N-implanted p-type 6H-SiC with a background carrier concentration of $\sim 10^{18}$ cm^{-3}. The samples were placed in a SiC crucible, which acted as a susceptor for absorbing microwave power and heating the 6H-SiC samples. In addition, the use of the SiC crucible protected the surface of the samples from pitting due to thermal dissociation caused by the evaporation of silicon. The crucible itself may also have some dissociation and hence maintained high Si partial pressure in the vicinity of the SiC sample during annealing. The SiC crucible was enclosed in an insulating material which minimized the heat loss from radiation and stabilized the temperature over the annealing cycle. Especially in the high temperature range of over 1300 °C, significant radiation loss would limit the maximum annealing temperature to be reached if the insulation were not used.

Arcing was one of the problems frequently encountered in the microwave annealing experiments. It was caused by an intense local electric field near a sharp corner or discontinuities of the crucible and insulation. A high and uncontrollable temperature caused by arcing could heat up the SiC samples to a temperature at which it would degrade and become useless for device fabrication. Therefore the geometry of the crucible and the insulation must be carefully designed to eliminate the arcing.

The sample was placed in the cavity and temperatures ranging from 1150 °C to 1400 °C were achieved in a few minutes. A typical temperature/time cycle obtained for 1230 °C annealing is shown in Fig 1. The temperature rose at a rate of ~300 °C/min and falls at a rate of ~200 °C/min, which is monitored by an optical pyrometer through a narrow orifice in the insulating case. Various gas ambients were tried during the annealing process. Argon and helium gases resulted in arcing at relatively low temperatures whereas nitrogen could withstand at least 1450 °C. The annealing was performed for a duration of 10-15 min after the temperature had been stabilized. After annealing, the samples were removed and subjected to a thorough cleaning process by solvents. A dip in HF is necessary to remove the nitride layer formed on the surface during annealing in the N_2 ambient. Hall measurements, Rutherford Backscattering (RBS), and photoluminescence measurements were performed on the annealed samples in order to evaluate the electrical activation of the implant as well as the lattice perfection.

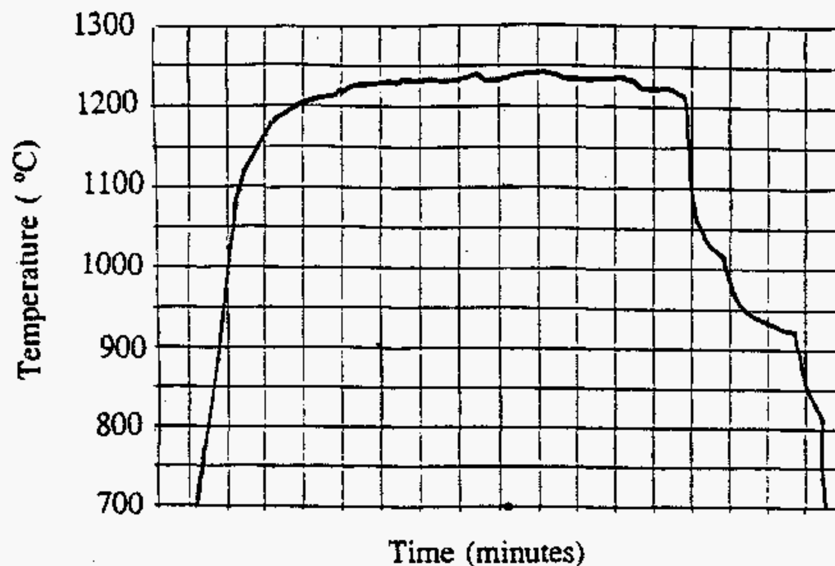

Fig.1. Typical temperature / time cycle of microwave annealing.

RESULTS

The N-implants were done at 700 °C down to a depth of 2.5 μm using a multiple ion energy schedule. The nitrogen implant schedule used was 50 keV/ 6.1x10^{13} cm^{-2}, 100 keV/ 9.2x10^{13} cm^{-2} , 250 keV/ 1.4x10^{14} cm^{-2} ,500 keV/ 1.6x10^{14} cm^{-2} , 800 keV/ 1.9x10^{14} cm^{-2}, 1 MeV/ 2.05x10^{14} cm^{-2}, 2 MeV/ 2.2x10^{14} cm^{-2}, 3 MeV/ 2.4x10^{14} cm^{-2}, and 4 MeV/ 2.67x10^{14} cm^{-2} in order to obtain a uniform nitrogen concentration of 10^{19} cm^{-3}. The as-implanted material is dark/opaque in color due to the lattice damage. Once annealed the samples regained their transparency with increasing annealing temperatures. No deterioration was observed in the surface morphology after annealing at 1400 °C.

The lattice perfection of the as-implanted and annealed samples was evaluated by performing RBS via channeling measurements. A 2.3 MeV He^{++} beam was used along with a standard solid-state detector which was positioned to record backscattered ions at 160°. Recorded spectra are shown in Fig. 2. Spectra from an aligned and randomly oriented virgin sample are also given in Fig. 2 to use as a basis for comparison with the RBS data. As shown in Fig. 2 the yield in the as-implanted sample is closer to the virgin level than to the random level. This random level indicates the scattering from a completely amorphized material. The low yield of the as-implanted sample is due to the implantation at an elevated temperature of 700 °C. Accumulated lattice damage is less at elevated implant temperatures due to dynamic self-annealing. This is in contrast to the room temperature implantation in which the as-implant yield would be at the random level [3]. After annealing at 1140 °C there is a significant reduction in the scattering yield, bringing the spectra closer to the virgin level. Nearly identical spectra were obtained for 1230 and 1320 °C anneals. For 1400 °C annealing, the spectra coincide with the virgin level indicating highly effective lattice damage removal. Similar RBS spectra were obtained on the samples annealed at 1500 and 1600 °C in the conventional Brew ceramic processing furnace.

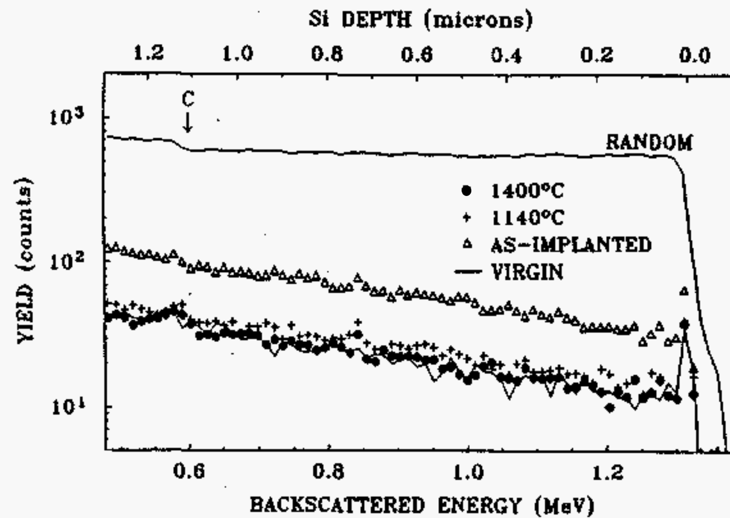

Fig. 2. RBS spectra on N-implanted SiC before and after annealing.

The electrical characteristics of the annealed material were evaluated by performing van der Pauw Hall measurements at room temperature. We were unable to perform Hall measurements on samples annealed at temperatures less than 1400 °C. This is due to the high resistance of the material associated with the residual implant damage. We observed a high resistance behavior in SiC bombarded with Si or C at levels which produce a high concentration of point defects. RBS provides a qualitative measure of gross lattice damage, which is in the form of extended defects like dislocation loops. Though the concentration of the extended defects is reduced at temperatures below 1400 °C, a large concentration of point defects, which cannot be detected by RBS, may still exist.

For the sample annealed at 1400 °C we measured a sheet resistance of $3x10^2$ Ω/□, a sheet carrier concentration of $5.6x10^{14}$ cm^{-2}, and a carrier mobility of 37 $cm^2/V.s$. The percent activation, which is obtained from the ratio of sheet carrier concentration and the total implant dose of $1.57x10^{15}$ cm^{-2}, was found to be approximately 36%. This activation is comparable to the values obtained [3] for conventional 1600 °C annealing. However the carrier mobility measured for 1400 °C microwave annealing is less than the value of 50 $cm^2/V.s$ obtained for the 1600 °C conventional annealing.

Photoluminescence measurements have also been taken in order to obtain addition information on the lattice quality of the sample as well as pair recombination information. Figure 3 shows the low temperature and low resolution photoluminescence (PL) spectrum of a p-type substrate, which has been implanted with N and microwave annealed at 1400 °C for 10 min. Also represented in the figure is the PL spectrum of the back-surface of the sample (un-implanted surface). The sharp lines observed in the spectral range between 3.0 and 2.8 eV, not clearly visible in the low resolution spectra shown in Fig. 3, are assigned to recombination processes involving the distribution of close N-donor and Al-acceptor pairs (close DAP recombination) present in the substrate. The broad shoulders detected between 2.85 and 2.65 eV are the zero

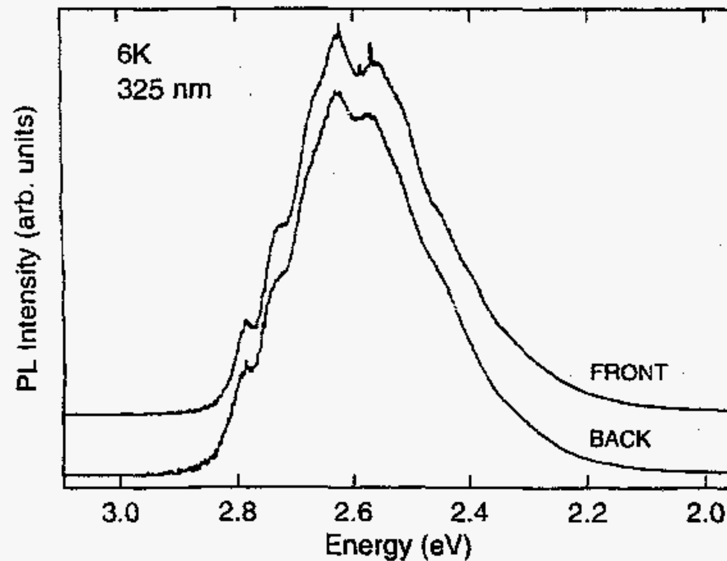

Fig. 3. Photoluminescence spectrum in implanted (front) and un-implanted (back) 6H-SiC.

phonon lines (ZPL) associated with the recombination of distant N-Al DAP. The only difference observed between the two spectra are the weak sharp lines at 2.623 eV, 2.588 eV, and 2.586 eV in the implanted sample. These lines are associated with defects induced by the ion implantation [9]. The relatively small intensity of these lines and the similarity between both spectra, suggested that the annealing treatment has recovered the crystalline quality of the substrate. Although the transport measurements performed on such layers shows conclusive evidence of N activation, we were not able to observe any emission band which could undoubtedly be assigned to the implanted N species. Since the penetration depth of the laser-line is much larger than the implanted layer thickness, we are planning to repeat this experiment with a high absorbing light source.

CONCLUSIONS

Microwave annealing seems to be an attractive method for rapid thermal annealing of implanted SiC. The electrical characteristics and lattice perfection of the annealed material are comparable to the values obtained for conventional ceramic processing furnace anneals.

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