Ion implantation of boron in germanium
Kevin S. Jones and E. E. Haller
Lawrence Berkeley Laboratory and University of California, Berkeley, California 94720

(Received 22 September 1986; accepted for publication 7 November 1986)

The activation of boron implanted at room temperature into germanium has been studied. In sharp contrast to all other group III elements boron forms a p-type layer before any postimplant annealing steps. Variable temperature Hall effect measurements and deep level transient spectroscopy experiments indicate that all of the boron ions are electrically active as shallow acceptor centers over the entire dose range (5×10^{11}/cm^{2} to 1×10^{14}/cm^{2}) and energy range (25–100 keV) investigated, without any postimplant annealing. The concentration of damage related acceptor centers is only 10% of the boron related, shallow accepted centers for low-energy implants (25 keV) but becomes dominant at high energies (100 keV) and low doses (<1×10^{12}/cm^{2}). Three damaged related hole traps are produced by ion implantation of ^{11}B^{+}. Two of these hole traps have also been observed in γ-irradiated Ge and may be oxygen-vacancy related defects, while the third trap may be divacancy related. All three traps anneal out at low temperatures (<300 °C). Room-temperature implantation of BF_{2}^{+} into Ge, does not lead to substitutionally active boron without annealing. A thermal cycle of 350 °C for 30 min activates 100% of the boron.

I. INTRODUCTION

Ion implantation of boron has proven to be invaluable in the fabrication of p^{+} contacts on ultrapure germanium. The problem with diffused contacts is one of contamination. Copper diffuses interstitially and forms a deep triple acceptor as well as complexing with hydrogen to form additional deep acceptors. At typical diffusion temperatures for germanium (600 °C) the solid solubility of Cu is ~2×10^{14}/cm^{2} or ~4 orders of magnitude above the background concentration. As no adequate p^{+} diffused contacts can be produced at low temperatures (<500 °C) in Ge the need for ion implanted contacts is apparent.

As summarized by Ponpon et al., boron appears to be the best group IIIA ion for the fabrication of p^{+} contacts in germanium due to its relatively small amount of damage production and the results of Alton and Love which have shown the resistivity of aluminum implants in Ge to be twice that of boron implants for anneal cycles below 450 °C and at a dose of 5×10^{14}/cm^{2} (a typical dose for a heavily doped contact).

Implantation of boron ions into germanium exhibits some unique phenomena. For every other ion implanted into silicon or germanium, some form of postimplant annealing step is necessary to achieve a significant electrical activation of the doping species. However, implantation of boron at a typical dose of 1×10^{14}/cm^{2} into germanium produces a peak acceptor center concentration of at least 1×10^{18}/cm^{2} prior to annealing. This concentration is sufficient to achieve a p-type contact without a postimplant annealing step. In fact, upon annealing the value of the sheet resistivity of a boron implanted layer shows no step decrease, characteristic of an implanted ion being activated. Others have reported different results of a small resistivity step and even a type change from n type to p type upon annealing. One of the questions that arises is, what is the source of the electrical activity associated with ion implantation of boron into germanium? Is the boron substitutional upon implantation and thus the source of the free holes or is the p-type conductivity due to lattice damage including possibly a variety of boron-defect complexes?

One reason for questioning the source of the conductivity, aside from its unusual annealing nature, is the published Rutherford backscattering (RBS) result which shows a damage peak for 30-keV boron ions implanted into germanium. This damage peak is shown to anneal away by 170 °C. Other observations include the effect of the temperature of the germanium during the implantation. As the substrate temperature drops from 130 °C to ~90 °C the normalized disorder increases from 3 to 100% for a 56 keV, 6×10^{14}/cm^{2} implant. This result implies that a significant amount of annealing occurs around room temperature. Additional RBS results indicate that implantation of boron into germanium produces 10 times as much damage as room temperature. It is known that a postimplant annealing step is required to electrically activate boron implanted into silicon. These two results might imply that the as implanted electrical activity of boron in germanium may be due to damage related acceptor centers.

From these results, it appears the nature of the electrical activity of implanted boron contacts on germanium is an issue worthy of further investigation.

II. EXPERIMENT: HALL EFFECT

Hall measurements are most commonly used to determine the free-carrier concentration. The Van der Pauw configuration, shown in Fig. 1, was chosen for our experiments. As the implanted layer is p type from either damage related acceptor centers or substitutional implanted boron, an n type (1×10^{13}/cm^{2}) substrate was used in order to isolate the implanted layer upon cooling of the sample. The german-
nium used was grown from a silica crucible under a hydrogen ambient and was doped with phosphorus. The isolation process involves the formation of a p-n junction at the depth where the implant p-type concentration equals the substrates' n-type doping. The electrical measurements are made via p-type (113) contacts which were implanted on the top surface corners and annealed prior to implanting the species to be studied. The wafer orientation was (113) and the sample was tilted 7° off axis during implantation. The germanium used is intrinsic at room temperature, therefore Hall effect measurements made at this temperature correspond to measuring the hole concentration in the implanted layer and the electron and hole concentrations in the intrinsic substrate. Upon cooling, the intrinsic carrier concentration decreases rapidly. Once the intrinsic carrier concentration is less than the n-type doping concentration of the substrate, electrons from the donor centers dominate the free-carrier concentration of the substrate. At this temperature, a p-n junction forms in the tail region of the implanted layer and at subsequently lower temperatures, only the implanted layer is measured via the p-type contacts.

III. RESULTS AND DISCUSSION

A. Implantation dose effects

In studying the effect of dose in these implantation experiments the energy of the implant was kept constant at 100 keV. The dose range investigated ranged from $5 \times 10^{11}$/cm$^2$ to $1 \times 10^{14}$/cm$^2$. The projected range for a 100-keV boron implant in Ge is around 2550 Å, with a standard deviation of 1150 Å. For a $1 \times 10^{14}$/cm$^2$ implant dose the peak concentration is about $3.5 \times 10^{18}$/cm$^3$ which is well above the Mott transition concentration. Thus, at this dose, conduction in the region whose concentration is above the Mott transition occurs via impurity banding due to the overlap of the electronic wave functions. The region of the implanted profile where the concentration is below the Mott transition affects the Hall coefficient and is responsible for the “dip” in concentration observed with VTHe of high dose

($ > 1 \times 10^{13}$/cm$^2$ for 100 keV) implants. This will be expanded upon later.

By reducing the dose to $1 \times 10^{13}$/cm$^2$ for a 100-keV implant the peak concentration drops below the Mott transition and observation of a “freezeout” slope of the thermally ionized free carriers becomes possible. At these low doses it is possible to use this slope to obtain information as to the binding energy of the centers creating the free carriers. Figure 2 shows variable temperature Hall effect plots for room temperature implants of boron at an energy of 100 keV and a dose of $5 \times 10^{13}$/cm$^2$. Implants at this low dose were compensated for noise pick up by the Faraday cups in the implanter. All annealing steps in these studies were performed in a quartz tube furnace under an argon atmosphere for 30 min. The intrinsic freeze out slope in Fig. 2, is indicated by the dark line. The concentration of acceptor centers in the unannealed sample is about $1.5 \times 10^{13}$/cm$^2$ or about three acceptor centers per incoming ion which are stable at room temperature. After annealing at 350 °C the concentration drops to around $8 \times 10^{11}$/cm$^2$. This decrease is due to the annealing out of damage induced acceptor centers. This will be further discussed later. The “freezeout” slope for both samples is the same when the free-carrier concentration drops below $5 \times 10^{11}$/cm$^2$ upon cooling. This slope corresponds to the “freezeout” of an uncompensated energy level 10–12 meV above the valence band, which matches well with the predicted half-slope “freezeout” of substitutional boron.

The variable temperature Hall effect plots for carbon and BF$_2$, also at an energy of 100 keV and a dose of $5 \times 10^{13}$/cm$^2$, are shown in Fig. 3. The steep deep level slopes are similar to those observed in the unannealed boron curve in Fig. 2. This indicates that at an energy of 100 keV and a

---

2470 J. Appl. Phys., Vol. 61, No. 7, 1 April 1987

K. S. Jones and E. E. Haller 2470

Downloaded 04 Apr 2011 to 128.227.135.101. Redistribution subject to AIP license or copyright; see http://jap.aip.org/about/rights_and_permissions
dose of $5 \times 10^{11}/\text{cm}^2$, the acceptor center concentration in boron, carbon, and BF$_2$ implants are all dominated by damage related centers. More damage is created by the BF$_2$ implant than the boron or the carbon implants. This is to be expected as the size and molecular weight of the BF$_2^+$ ion is much greater than the B$^+$ and C$^+$ ions. The effect of annealing the BF$_2$ implant is seen in Fig. 4. The slope decreases as the deep damage related acceptor levels are annealed out and the boron is annealed into substitutional sites. If the boron were substitutional in the “as-implanted” BF$_2$ implant as it is in the boron implant then the slope of the BF$_2$ implant (Fig. 4) should change abruptly to a shallow boron “freeze-out” slope as the free-carrier concentration drops below $5 \times 10^{11}/\text{cm}^2$. As the slope is still quite steep below $5 \times 10^{11}/\text{cm}^2$, it is concluded that the boron in the BF$_2$ implant is not completely substitutional upon implantation and must be “activated” by an annealing step.

Figure 5 shows the effect of annealing on the total acceptor center concentration for all three implants at the implant energy of 100 keV and dose of $5 \times 10^{11}/\text{cm}^2$. The concentration was determined by the point at which the slope changed from an intrinsic freeze out to a shallower slope. The difficulty in determining exactly where the slope changes from the intrinsic slope to the acceptor center “freezeout” slope is expressed in the error bars shown. Implants of all three species exhibited an increase in the defect concentration upon annealing at 225 °C. This may arise from the formation of additional defects due to increased diffusion of one of the species involved in the defect. This increase is also observed with DLTS. As will be seen, with our geometry, DLTS of these implanted layers does not yield an absolute concentration of the damage centers. Upon annealing there is observed a relative increase in the $\Delta C/C$ values (peak heights) which correlates well with the increase in acceptor center concentration observed with Hall effect. Annealing at temperatures above 250 °C for 30 min dissociates the defect and above 350 °C the carbon implanted samples return to being n-type.
i.e., the $p$-type damage is annealed such that the background $n$-type doping is dominant. Subtraction of the carbon damage related acceptor center concentration from the boron related acceptor center concentration does not yield accurate quantitative information on the boron concentration as observed by the slope change in Fig. 5, noted previously. One explanation for this may be that carbon implants produce a slightly greater concentration of damage related acceptor centers, which are stable at room temperature, than the boron implants. Thus, at this low dose, the carbon implants may have limited quantitative application to boron implants, but the qualitative annealing behavior for boron and BF$_2$ implants is sufficiently similar to the carbon implants behavior to conclude that damage related acceptor centers do indeed dominate this low dose, high implant energy extreme. The concentration of acceptor centers in the boron implanted samples drops to about $5 \times 10^{11}/\text{cm}^2$ by 550°C while the concentration of acceptor centers in the BF$_2$ implanted samples drops only to $8 \times 10^{11}/\text{cm}^2$. The difference in concentration may arise from some electrically active defect associated with fluorine.

Contamination problems occurred for anneal temperatures above 600°C. Additional investigations indicate that the $n$-type substrate changes to $p$-type at about 600°C due to Cu contamination. Precautions were taken to avoid contamination including a slow postannealing cooling step to avoid "quenching in" large Cu concentrations by promoting Cu precipitation.

The effect of increasing the dose on the acceptor center concentration in boron and carbon implanted samples is shown in Fig. 6. All samples were implanted at room temperature and were measured in the "as implanted" state. As the dose increases the number of defect-related, acceptor centers, stable at room temperature, per incoming ion decreases. However, the concentration of acceptor centers arising from shallow acceptor levels becomes constant at one per incoming boron ion at doses above $1 \times 10^{13}/\text{cm}^2$. As we have just concluded that the boron is substitutional "as implanted" at the low dose extreme, Fig. 6 indicates that for a room temperature 100-keV implant the boron is active upon implantation over the entire range of doses studied. Any increase in free carriers at low doses must arise from damage related acceptor levels and the concentration of these levels is greater than the concentration of shallow boron related acceptor levels at doses below $1 \times 10^{12}/\text{cm}^2$.

The variable temperature Hall effect results for a 100-keV boron implant at a dose of $1 \times 10^{14}/\text{cm}^2$ are shown in Fig. 7. Implants of 100-keV boron into Ge at doses greater than $1.5 \times 10^{13}/\text{cm}^2$ yield peak concentrations above the Mott transition and banding conduction occurs. For bulk Ge doped above $5 \times 10^{17}/\text{cm}^3$, the Hall coefficient, $R_H$, is independent of temperature. However, as seen in Fig. 7, for implanted layers the Hall coefficient is not independent of temperature between 200 and 10 K. This deviation can be explained theoretically by the following equation. Assuming there are no circulating currents and $\rho_H = \mu$ the surface Hall coefficient, $R_s$, can be expressed as

$$R_s = \frac{\int_0^1 n(x)\mu^2(x)dx}{e(\int_0^1 n(x)\mu(x)dx)^2},$$

where $n(x)$, $\mu(x)$ are the concentration and the mobility as a function of depth, respectively. The junction depth is $t$ and $e$ is the change of an electron.

Upon cooling through the upper temperature region (200 K > $T$ > 30 K) the rapidly increasing mobility of the lower doped regions (those around the peak with concentrations less than $1 \times 10^{16}/\text{cm}^3$) contribute significantly to increasing the value of $R_s$. Upon further cooling the carriers in these lower doped regions (those not above the Mott transition) "freezeout" and these high mobility regions become

![FIG. 6. Net acceptor concentration as a function of implant dose for 100-keV implants into Ge prior to annealing.](image)

![FIG. 7. Carrier freezeout as a function of inverse temperature for a 100-keV boron implant of dose of $1 \times 10^{14}/\text{cm}^2$.](image)
less of a factor in the value of $R_s$. The Hall coefficient upon cooling through this region ($30 \text{K} > T > 10 \text{K}$) decreases to a value characteristic of just measuring the region of the implant above the Mott transition. The mobility of the highly doped region is relatively independent of temperature through this whole temperature range ($200 \text{K} > T > 10 \text{K}$).

A rough estimate of the Hall coefficient, using the above equation, was calculated by dividing the implanted region into 17 sections of equal thickness and evaluating the integrals as sums of all the sections. For example, Fig. 8 is a combination of free-carrier concentration and Hall mobility as a function of inverse temperature for a bulk germanium sample doped with $2 \times 10^{14} / \text{cm}^3$ gallium. In order to accurately determine the theoretical Hall coefficient curve, a plot such as this would be necessary for each section of the implant. The published values for the mobility as a function of temperature and concentration for $p$-type Ge just below the Mott transition are incomplete. As such, interpolation of mobility values was used and the low temperature values ($T < 30 \text{K}$) became less accurate for concentrations between $5 \times 10^{15} / \text{cm}^3$ and $5 \times 10^{17} / \text{cm}^3$. The results of the calculations are shown in Fig. 9 along with the actual experimental data for both a bulk sample and the implanted sample. The value of the bulk sample corresponds to the average concentration over the entire implanted layer. With no fitting parameters the initial high-temperature theoretical values ($T > 100 \text{K}$) are in good agreement with experimental values and the qualitative effect of temperature on the value of $R_s$ is explained. The deviation in the quantitative theoretical values at lower temperatures may arise from inaccurate mobility and concentration values as a function of temperature in the concentration region discussed above or they may arise from deviation of the actual implant profile from its assumed Gaussian shape due to perhaps random channeling.

BF$_3$ implants at 100 keV and a dose of $1 \times 10^{14} / \text{cm}^2$, however, exhibit a very different behavior from boron implants as seen in Fig. 10. Prior to annealing the dominant acceptor centers are deep level damage-related defects whose concentration is about $5 \times 10^{15} / \text{cm}^3$ or 0.5 electrically active defects per incoming ion and whose energy levels will be discussed in the DLTS section. Upon annealing at 350 °C for 30 min the boron becomes electrically active and, as confirmed by DLTS, the damage is annealed out.

---

**FIG. 8.** Free-carrier freezeout and Hall mobility as a function of inverse temperature for a bulk Ga:Ge doped sample.

**FIG. 9.** The Hall coefficient as a function of inverse temperature for a 100-keV boron implant in Ge at a dose of $1 \times 10^{14} / \text{cm}^2$.

**FIG. 10.** Carrier freezeout as a function of inverse temperature for 100-keV BF$_3$ implanted into Ge at a dose of $1 \times 10^{14} / \text{cm}^2$. 

---

2473 J. Appl. Phys., Vol. 61, No. 7, 1 April 1987

K. S. Jones and E. E. Haller 2473
B. Implantation energy effects

What role does implant energy play in the question of the dominant energy level created by boron implantation? As was noted above, for 100 keV implants the damage related acceptor level concentration does not exceed the substitutional boron acceptor concentration until the dose is below around $1 \times 10^{12}$/cm$^2$. Figure 11 shows the effect of changing the energy of carbon implants in the dose range of interest. As one increases the energy, the number of stable defects, for a given dose, increases. This trend is predicted by LSS theory as there is more energy to create defects.

Independent of the dose, at low energies (25 keV) the number of defects per incoming ion is small. This is confirmed by Fig. 12. Again the boron is active “as implanted” and no significant change was observed upon annealing. From these results one could predict that a low dose ($5 \times 10^{11}$/cm$^2$) low-energy (25 keV) implant should show only substitutional boron in the “as-implanted” state. This is observed in Fig. 2. The slope of the “freezeout” line corresponds well to the expected uncompensated “freezeout” slope of a shallow acceptor such as substitutional B in Ge. The reason no plateau is observed as was the case at 100 keV is that the energy is less, therefore the peak concentration is greater for the same dose implant. It can thus be concluded that about 100% of the boron appears to be substitutional upon room temperature implantation at all doses and all energies studied. In addition, the relative concentration of damage related acceptor centers becomes significant at low doses and high energies.

The next question concerns the nature of this electrically active damage created by boron implantation. The best experimental method to further investigate these deep acceptor levels proved to be deep level transient spectroscopy.

\[\text{FIG. 11. Damage concentration as a function of implant dose for several implant energies.}\]

\[\text{FIG. 12. Carrier freezeout as a function of inverse temperature for 25-keV boron implants at a dose of}\ 1 \times 10^{13}/\text{cm}^2.\]

IV. EXPERIMENT: DEEP-LEVEL TRANSIENT SPECTROSCOPY

DLTS\textsuperscript{10} is the most common of the space charge capacitive transient spectroscopy techniques. The geometry that eventually worked is shown in Fig. 13. Detector grade germanium was used which was grown from a silica crucible under a hydrogen ambient. The p-type substrate doping was $1 \times 10^{10}$/cm$^3$. The sample thickness was 220 $\mu$m. First, a p-n junction was fabricated on one side of the slice. This was done by implanting the sample with $1 \times 10^{14}$ 25P/cm$^2$ at 25 keV. The implantation was done at 77 K. Next the sample was annealed at 400 °C in argon for 30 min to “activate” the phosphorus and anneal out any implant damage. In order to make sure none of the damage from the phosphorus implant remained, a gold ohmic contact was deposited on the side opposite the p-n junction and subsequent DLTS measurements showed no deep levels present in the spectrum. Finally the implant to be studied was done into the side opposite the p-n junction prior to the deposition of a gold ohmic contact. The implant energy was 190 keV and the dose was $1 \times 10^{13}$/cm$^2$. It is desirable to know what reverse bias vol-

\[\text{FIG. 13. DLTS sample geometry for study of implanted layers in Ge. A: Substrate p-type Ge } N_a - N_d = 1 \times 10^{17}/\text{cm}^2. \text{ B: Phosphorus implanted contact 25 keV } 1 \times 10^{14}/\text{cm}^2, \text{ annealed 400 °C for } 30 \text{ min. C: Implant to be studied 190 keV } 1 \times 10^{13}/\text{cm}^2. \text{ D: Evaporated Au ohmic contact.}\]

2474 J. Appl. Phys., Vol. 61, No. 7, 1 April 1987
K. S. Jones and E. E. Haller 2474
tage is sufficient to deplete through the entire implant. In order to estimate this it is necessary to solve Poissons' equation for this geometry. This was done numerically and the solution is shown in Fig. 14 (dashed line). As is seen in the figure, a reverse bias of 0.27 V is sufficient to deplete the 220-μm-thick substrate and a reverse bias of 12 V would deplete almost entirely through a 190 keV, 100% active, boron implant at a dose of 1 x 10^13/cm². A reverse bias of 8 V with a pulse of 7.4 V was used in the following experiments.

V. RESULTS AND DISCUSSION

Figure 15 shows a comparison between 190 keV implants of boron and carbon at a dose of 1 x 10^13/cm². The lowest spectrum shows a boron implant in the "as-implanted" condition. The middle spectrum is of the same boron sample upon annealing at 140 °C for 30 min, while the top spectrum is of a carbon implanted sample in the "as-implanted" condition. All three spectra exhibit the same peaks except for the appearance of H4 in the carbon implanted sample. This implies that none of the damage peaks H1, H2, or H3 are boron related. It was not possible to determine the absolute concentration of these defects as the capacitance of the bulk dominates any C-V measurements and thus the background concentration is unknown. However, as will be shown, annealing studies imply that the peaks H1 and H2 are indeed the dominant damage related acceptor centers observed with Hall effect. Table I lists the energy levels and cross sections for the various peaks. The capture cross sections were determined from the y intercept of an Arrhenius plot of the logarithm of the correlator time constant as a function of inverse peak temperature. The more direct method of measuring the change in trap filling as a function of pulse width could not be used as the background concentration is the implanted profile which is not accurately known. The hole traps H1, H2, and H3 also appear in samples implanted with BF₂⁺, N⁺, O⁺ and Ne⁺, which further indicates that they are independent of the species implanted.

In Fig. 15 it is seen that the trap peak heights increase when the sample is annealed at low temperatures (< 250 °C). This annealing behavior is summarized in Fig. 16 and results for the larger peaks H1 and H2 correlate well with the observed increase in concentration of the damage related acceptor levels in the low dose variable temperature Hall effect experiments discussed earlier (Fig. 5). In general, prior to annealing, the peaks for the boron implanted samples were smaller than the carbon implanted samples. This may be due to a slightly greater concentration of damage-related acceptor centers noted with low dose Hall effect results in Fig. 6, however it does not necessarily mean that the concentration of traps is greater, as the value of ΔC/C depends on both the number of traps and the average background doping in the region being observed with the pulse. Both of these are unknown, thus only relative changes in the ratio of these two unknowns can be observed with DLTS. Variable temperature Hall effect experiments indicate the free-carrier concentration in carbon implanted samples "freezes-out" rapidly upon cooling while the free-carrier concentration in boron implanted samples remained high. If the trap concentration were the same in the two samples, the value of ΔC/C, and thus the peak height, would be greater in the carbon implanted sample. If the shallow acceptor concentration is fairly constant upon annealing as the boron Hall effect experiments indicate, then the change in ΔC/C plotted in Fig. 16 should correlate reasonably well with the relative change in the trap concentration upon annealing. By 250 °C, both H1 and H2 have annealed away. This annealing behavior was observed regardless of the implant species.

The total capacitance of the sample (under a reverse bias ≥ 0.5 V) is dominated by the capacitance of the bulk, not the implant region which is being filled and depleted of

<table>
<thead>
<tr>
<th>TABLE I. Energy levels and cross sections for various peaks.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Label</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>H1</td>
</tr>
<tr>
<td>H2</td>
</tr>
<tr>
<td>H3</td>
</tr>
</tbody>
</table>

FIG. 14. Calculated voltage drop through a 190-keV boron implant of 1 x 10^13/cm² into Ge.

FIG. 15. DLTS spectra of 190-keV boron and carbon implants in Ge.
free carriers. The total capacitance change upon pulsing the voltage (i.e., 8 V rev bias pulsing 7.5 V forward bias) is very small and accordingly the value of $\Delta C$ relative to the $C$ of the bulk is also very small. Thus, a small $\Delta C / C$ does not necessarily mean a small trap concentration.

The energy levels and capture cross sections of $H1$ and $H2$ match quite well with two hole traps observed by Pearton et al.\(^{11}\) They found the same acceptor levels in $\gamma$-irradiated Ge and concluded they are oxygen-vacancy related complexes. To further substantiate the theory that $H1$ and $H2$ are the same peaks Pearton et al. observed, the annealing characteristics of both sets of peaks are identical.

The hole trap $H3$ is observed to anneal out between 150–200°C. Bourgoin et al.\(^{12}\) have observed a hole trap with the same depth and similar annealing characteristics, using DLTS to study room temperature electron irradiated $n$-type germanium. They associate this hole trap and two electron traps with the divacancy.

The preliminary identification of all three hole traps $H1$, $H2$, and $H3$ is consistent with the observation of the traps being associated with damage induced, species independent levels. Variable temperature Hall effect investigations using implantations of oxygen as well as other species are in progress to help determine if the major damage related acceptor centers involve oxygen. Sources of oxygen such as “knock-on” oxygen from the surface and oxygen grown into the crystal must be recognized in interpreting the results.

Upon annealing at higher temperatures (> 300°C), Cu peaks were observed to grow confirming our suspicion that Cu contamination was the reason for the substrate conversed observed upon high-temperature annealing of VTHE samples.

VI. CONCLUSIONS

$^{11}$B\(^+\), $^{12}$C\(^+\), and BF\(_2\)\(^+\) ions implanted into Ge were studied using two techniques. Carrier concentration of the implanted layers as a function of implantation species, implantation dose, implantation energy, and postimplant annealing temperature have been investigated using Hall effect. The characterization of the damage created upon implantation using DLTS was also presented.

The results of the experiments on boron implants indicate that over the entire dose range ($5 \times 10^{11}$/cm\(^2\) to $1 \times 10^{14}$/cm\(^2\)) and energy range (25–150 keV) studied, 100% of the boron ions are substitutionally active upon implantation at room temperature. For low-energy implants (25 keV) of boron the concentration of stable damage related acceptor centers is significantly less than the concentration of shallow boron related acceptor centers over the entire dose range studied. As the implantation energy increases the concentration of damage related acceptor centers per incoming ion also increases. This increase in damage is more significant at lower doses than at higher doses. Thus, at 100 keV, the concentration of damage related acceptor centers becomes greater than the concentration of shallow boron related acceptor centers at doses below $1 \times 10^{12}$/cm\(^2\).

The damage related acceptor centers consist of three hole traps, $H1$, $H2$, and $H3$. None of these traps are associated with boron. Upon annealing below 225°C the concentration of $H1$ and $H2$ appears to increase. Annealing for 30 min at temperatures above 250°C results in the elimination of $H1$ and $H2$. Hole trap $H3$ is annealed away after 30 min at 150°C. The hole traps $H1$ and $H2$ have been observed before by Pearton et al.\(^{11}\) in DLTS studies on $\gamma$-irradiated Ge. They concluded these are oxygen-vacancy related defects. $H3$ appears to be the same hole trap observed by Bourgoin et al.\(^{12}\) in electron irradiated Ge. They suggested that it may be associated with a divacancy.

The boron in BF\(_2\) implants is not electrically active upon room-temperature implantation within the dose range and energy range discussed above. The same three hole traps, $H1$, $H2$, and $H3$, are observed. Upon annealing at 350°C for 30 min the damage is repaired and the boron is substitutional.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Nancy Haegel for the many helpful discussions and Dick Chan for doing all of the implantations. This work was supported in part by the National Science Foundation, Grant DMR-8203430 and in part by the Director's Office of Energy Research, Office of Health and Environmental Research, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
