Modeling Changes in Measured Conductance of Thin Boron Carbide Semiconducting Films Under Irradiation

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Abstract—Semiconducting, p-type, amorphous partially dehydrogenated boron carbide films (a-B10C2+x:Hy) were deposited utilizing plasma enhanced chemical vapor deposition (PECVD) onto n-type silicon thus creating a heterojunction diode. A model was developed for the conductance of the device as a function of perturbation frequency (f) that incorporates changes of the electrical properties for both the a-B10C2+x:Hy film and the silicon substrate when irradiated. The virgin model has 3 independent variables (R1, C1, R3), and 1 dependent variable (f). Samples were then irradiated with 200 keV He+ ions, and the conductance model was matched to the measured data. It was found that initial irradiation (0.1 displacements per atom (dpa) equivalent) resulted in a decrease in the parallel junction resistance parameter from 6032 Ω to 2705 Ω. Further irradiation drastically increased the parallel junction resistance parameter to 39000 Ω (0.2 dpa equivalent), 77440 Ω (0.3 dpa equivalent), and 190000 Ω (0.5 dpa equivalent). It is believed that the initial irradiation causes type inversion of the silicon substrate changing the original junction from a p-n to a p-p+ with a much lower barrier height leading to a lower junction resistance component between the a-B10C2+x:Hy and irradiated silicon. Additionally, it was found that after irradiation, a second parallel resistor and capacitor component is required for the model, introducing 2 additional independent variables (R2, C2). This is interpreted as the junction between the irradiated and virgin silicon near ion end of range.

Index Terms—Alpha particle radiation, Conductance, Hydrogenated boron carbides, Neutron detector, p-n heterojunction, Semiconducting boron carbides.

NOMENCLATURE

PECVD Plasma enhanced chemical vapor deposition.
D Dissipation factor.
G Conductance.
Gm Measured conductance.
G0 Low frequency conductance.
Cp Equivalent parallel circuit capacitance.

ω Angular frequency (ω = 2πf).
f Small signal perturbation frequency.
CINT Center for Integrated Nanotechnologies.
LANL Los Alamos National Laboratory.
SRIM Stopping and range of ions in matter.
DPA Displacements per atom.
a-B10C2+x:Hy Semiconducting amorphous partially dehydrogenated boron carbide film.
Z Equivalent complex impedance.
Y Complex admittance.
C1 1st Parallel capacitance component: interpreted as a-B10C2+x:Hy dielectric film.
R1 1st Parallel junction resistance: interpreted as a-B10C2+x:Hy/Si and/or a-B10C2+x:Hy/Cr interface(s).
C2 2nd Parallel capacitance component: interpreted as depletion region between irradiated Si/virgin Si interface.
R2 2nd Parallel junction resistance component: interpreted as silicon p-n homojunction near ion end of range.
R3 Series resistance of device including quasi-neutral region of Si substrate, contact resistance of anode & external circuitry.
TEM Transmission electron microscopy
V2 Di-vacancy state.
ρ Resistivity.
q Elementary charge.
μp Hole mobility.
NA Doping concentration of acceptors in a p-type film.
R Resistance.
L Film length.
W Film width.
t Film thickness.

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I. INTRODUCTION

Semiconducting boron carbide icosahedral materials have been the subject of investigation for solid state neutron detection [1-12] and as a neutron voltaic for some time [13,14]. A device capable of generating a current pulse from a neutron impact must be capable of tolerating any damage caused by the impact with adverse effects to device efficiency. Boron rich icosahedrals such as boron carbide [15-19], boron nitride [20,21], and boron phosphide [22,23] materials are particularly advantageous in certain situations, such as neutron detection and neutron voltaics, due to their ability to heal neutron [15], electron [19,22,23], and He⁺ ion [24] irradiation damage. There have been many structural studies of radiation on boron carbides [15,23,25-31] as hot-pressed/sintered, powdered or sputtered samples. Our previous paper [24], which showed that heterojunction device performance improved with moderate amounts of He⁺ ion irradiation, was the first to study the effects of radiation on amorphous boron carbides as an electrical device. The ramifications of the physical changes on the electrical properties of semiconducting boron carbides have not been examined.

Heterojunction diodes created from plasma enhanced chemical vapor deposition (PECVD) of ortho-carborane (closo-1,2 dicarbododecaborane, C₂B₁₀H₁₂) resulting in p-type semiconducting partially dehydrogenated boron carbide on n-type silicon (100) suffer from limits in current rectification efficiency due to high defect concentrations [32] and low carrier mobilities [33]. This leads to a constant power drain through the device, inefficient charge collection, and low sensitivity as a neutron detector or low efficiency as a neutron voltaic. These intrinsic properties of PECVD semiconducting partially dehydrogenated boron carbide on silicon p-n heterojunction diodes may be improved as degraded icosahedral structures (icosahedral carbaborane molecules, B₉₀C₂H₁₂, missing B and H atoms) heal under neutron, electron, and He⁺ ion irradiation. If the defect concentration is reduced, and the charge carrier mobility is increased with irradiation, this could lead to a much more efficient device the longer the device is in service, even in extremely radiation harsh environments.

Boron based thermal neutron detectors and neutron voltaics are capable of operation due to a capture-fragmentation-emission process with daughter fragment particles ⁷Li, He⁺, with large translational energy. The energetic ⁷Li and alpha fragments deposit energy in the semiconducting partially dehydrogenated boron carbide and the silicon substrate. There are 2 main means of energy deposition. The first is due to electronic stopping (ionization/excitation). The incident ion represents a sudden perturbation to the system resulting in a transfer of energy from the projectile to the electrons of the target material [35] which can lead to bond breaking. The second form of deposition is due to energy transfer through the elastic collisions (recoil) between the projectile ion and the atoms of the target material. This energy deposition can result in atomic displacements, ultimately leading to damage accumulation.

One of the more common ways to characterize a semiconductor device is through capacitance vs frequency and capacitance vs voltage measurements with a small ac perturbation signal imposed across the device under test in a 4-point parallel circuit utilizing an impedance analyzer. This works well for devices with efficient charge separation and negligible conductance. However, if the device is highly trapped, or has a high defect concentration, the contributions to the capacitor charging current are no longer negligible. These so-called “leaky diodes” are not always accurately characterized using the capacitance measurements mentioned above because their dissipation factor (D) becomes excessive

\[ D = \frac{G}{\omega C_p} \]  

where \( G \) is conductance, \( \omega \) is angular frequency (\( \omega = 2\pi f \)), \( f \) is small signal perturbation frequency, and \( C_p \) is equivalent parallel circuit capacitance. In the case of a large dissipation factor (\( D > 10 \)), a more suitable measurement is conductance vs frequency or conductance vs voltage. This paper seeks to determine the conductance as a function of frequency, and compare the calculated values to experimental data to examine changes in the electrical properties of the semiconducting partially dehydrogenated boron carbide as a function of radiation. For reference, the dc current vs voltage (I/V) curves as a function of irradiation have been included as Appendix A, and are reprinted with permission (License Number 3961511243923) [24].

II. EXPERIMENTAL DETAILS

Device fabrication begins with an n-type silicon (P doped) substrate (100) with resistivity of 1-10 Ω·cm (purchased from Silicon Inc., Boise, ID). Substrates are cleaned in sequential baths of acetone, methanol, de-ionized water, and 5 wt% hydrofluoric acid for hydrogen termination [36]. The semiconducting amorphous partially dehydrogenated boron carbide films are synthesized via plasma enhanced chemical vapor deposition (PECVD) utilizing ortho-carborane (closo – 1,2 dicarbododecaborane, C₂B₁₀H₁₂) as the precursor (purchased from Sigma Aldrich). Details of the deposition process were previously reported [24,37]. The reported stoichiometric compositions of semiconducting amorphous partially dehydrogenated boron carbide films have varied widely [8,38,39]. This is represented by \( a\text{–}B_{10}C_{2+x}H_y \) with \( 0 < x < 3 \) and \( 0 < y < 12 \). For this study, according to elastic recoil detection measurements, \( x \) is approximately 0, and \( y \) is approximately 4.

Irradiation was completed at the Center for Integrated Nanotechnologies (CINT), within Los Alamos National Laboratory (LANL) using a 200 kV Danfysik implanter. 200 keV He⁺ ions were implanted to a fluence of \( 6.5 \times 10^{18} \) ions/cm² with the He⁺ ion beam current density of \( -4.4 \) μA/cm². Air-cooling was applied to ensure that the sample temperature remained below 40° C during irradiation.

As previously reported [24], through the application of the Monte Carlo SRIM simulation (stopping and range of ions in matter code) [35] an ion range of ~1400 nm was projected for...
200 keV He\(^+\) ions. Also reported [24], one aliquot of fluence (i.e. 6.5\(\times\)10\(^{16}\) ions/cm\(^2\)) was calculated to result in 0.1 displacements per atom (dpa) in the a-B\(_{10}C_{2\times3}\)H\(_2\) films studied. The fluence to dose (dpa) relationship is linear: 2 times the above fluence yields 0.2 dpa in dose, etc.

Following irradiation, the samples were returned for electrical characterization. Conductance versus frequency \(G(f)\) measurements were taken using an HP model 4192A impedance analyzer with an oscillation voltage set to 0.010 v in a 4 point parallel circuit. The analyzer has 4 parallel connections. From left to right, they are: low current, low potential, high potential, high current. By creating a metal housing for the diode under test and connecting the housing directly to the analyzer through un-insulated BNC connectors, the negative portion of the 4 connections are grounded to the analyzer creating an RF shield around the diode under test. The 4192A impedance analyzer has a conductance measurement range of 1\(\times\)10\(^{-9}\) \(\Omega\) to 12.999 \(\Omega\) with an accuracy of 0.1\%, and a resolution of 4 \(\frac{1}{2}\) digits for both grounded and floated devices.

III. RESULTS

![Fig. 1. Circuit model used in analysis. R1 and C1 represent the resistance and capacitance of the a-B\(_{10}C_{2\times3}\)H\(_2\). R2 and C2 represent the resistance and capacitance of the silicon, and R3 represents series resistance.](image)

Table I shows the results obtained for the fitting parameters of equation (2). As stated earlier, the virgin device was capable of being modeled with only the parameters of C1, R1, and R3. After moderate irradiation to 0.1 dpa, a 2\(^{nd}\) parallel resistive (R2) and capacitive (C2) component is required. Table I shows these values to be 40 \(\Omega\) and 1.166\(\times\)10\(^{-9}\) F. Additionally, the resistance of R1 is reduced by 55.2\%. Irradiation to 0.2 dpa in the a-B\(_{10}C_{2\times3}\)H\(_2\) film, results in a dramatic increase in resistance R1 of 1341.8\%. Irradiation to 0.3 dpa in the a-B\(_{10}C_{2\times3}\)H\(_2\) film, results in another dramatic increase in resistance parameter R1 of 98.6\%. Further irradiation to 0.5 dpa in the a-B\(_{10}C_{2\times3}\)H\(_2\) film, continues the trend of another dramatic increase in the resistance parameter R1.

Table I. Fitting Parameter Values of Equation (2)

<table>
<thead>
<tr>
<th>Sample</th>
<th>(\frac{\sigma_1}{\sigma_4})</th>
<th>(\frac{\sigma_2}{\sigma_4})</th>
<th>(\frac{\sigma_3}{\sigma_4})</th>
<th>(\frac{\sigma_4}{\sigma_4})</th>
<th>(\chi^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin</td>
<td>0.0006360</td>
<td>0.0003835</td>
<td>0.0006360</td>
<td>0.0004651</td>
<td>0.0003835</td>
</tr>
<tr>
<td>0.1 dpa</td>
<td>0.0001278</td>
<td>0.0001278</td>
<td>0.0001278</td>
<td>0.0001278</td>
<td>0.0001278</td>
</tr>
<tr>
<td>0.2 dpa</td>
<td>0.0004651</td>
<td>0.0004651</td>
<td>0.0004651</td>
<td>0.0004651</td>
<td>0.0004651</td>
</tr>
<tr>
<td>0.3 dpa</td>
<td>0.0008379</td>
<td>0.0008379</td>
<td>0.0008379</td>
<td>0.0008379</td>
<td>0.0008379</td>
</tr>
</tbody>
</table>

\(C_1\) is interpreted as the capacitance due to the a-B\(_{10}C_{2\times3}\)H\(_2\) dielectric film. \(R_2\) is interpreted as the a-B\(_{10}C_{2\times3}\)H\(_2\)/Si junction resistance and a-B\(_{10}C_{2\times3}\)H\(_2\)/Si/Cr contact resistance. C2 is interpreted as the Si(Irradiate)/Si(virgin) homojunction capacitance, R2 is interpreted as the junction resistance of the Si(Irradiate)/Si(virgin) homojunction, and R3 is interpreted as the equivalent series resistance of the device. \(\chi^2\) is the chi square goodness-of-fit-test statistic. A \(\chi^2\) value < 0.412 corresponds to a 99.5\% confidence level.
increase in the resistance of parameter R1 of 145.4%.

The parameter interpreted as the equivalent series resistance of the device (R3) remains within the expected range calculated for the quasi-neutral silicon substrate of 26 to 260 Ω based on the resistivity range provided by the manufacturer. The changes of R3 listed in Table 1 are not viewed as a significant deviation. Changes in the fitting parameters C1 and C2 of tenths of a nanofarad, are not viewed as significant deviations as the device is irradiated. Changes in the parallel resistance parameter R2 follow the general pattern of R3, and are interpreted as minor changes in the carrier concentration profile inherent to the substrate rather than a result of changes due to irradiation.

When the modeled conductance is overlaid on the measured data on a linear scale, the two are nearly indistinguishable. This is indicated by the chi square goodness-of-fit-test statistics with values 3 orders of magnitude less than the value corresponding to a 99.5% confidence interval. Fig. 2 shows the measured conductance versus frequency and overlaid modeled conductance versus frequency curves on a Log-Log scale. Using the Log-Log scale, Fig. 2 shows that the low frequency conductance (G0), is unique for each level of irradiation. Examination of Fig. 2 also shows that the frequency at which charge carriers can no longer respond to the perturbation signal (indicated by an increase in conductance) decreases as the level of irradiation damage increases. For the virgin sample, this is just above 10^4 Hz, but for the 0.5 dpa sample, there are charge carriers that cannot respond to a 10 Hz signal. The slope of the curves between 2×10^4 Hz and 1 MHz is unique to each level of irradiation. The upper limit of conductivity, as frequency approaches infinity (f → ∞), consolidates into a narrow band. A difference between the virgin and irradiated samples exists.

IV. DISCUSSION

The Mathworks® Matlab curve fitting toolbox was utilized to determine the best values for the independent parameters of equation (2) (C1, R1, C2, R2, R3), as a function of the perturbation frequency utilizing bisquare weighting, which gives the strongest weighting to data points near the fit, and low weighting to outlying data points. In fitting the data to obtain the results of Table 1, parts of the model are very sensitive to specific variables of equation (2). In the low frequency range, below 10 kHz, although the limit of Gm as frequency approaches 0 (f → 0) is inversely proportional to R1 + R2 + R3, it is only sensitive to changes in R1 (resistance of the original R1, C1 parallel component). In the high frequency range, the limit of Gm as frequency approaches infinity (f → ∞) is inversely proportional to R3 (equivalent series resistance of the device). The initial upturn in conductance is dominated by C1. And the slope between the upper and lower limits of conductance is dominated by R2 and C2 (The resistance and capacitance of the 2nd parallel RC component).

The model does not fit the low frequency conductance particularly well for the samples irradiated above 0.3 dpa. Previously published TEM images [24] show a direct correlation between the SRIM calculated vacancy profile and the damage to the Si substrate as well as between He bubble formation and the SRIM calculated peak of the He distribution profile. The TEM images also provided visual evidence of point defect agglomeration. These structural changes in the Si substrate provide visual indications that di-vacancy states (V2), formed by the combination of vacancies created in close proximity to each other, and other vacancy complexes, allow us to infer that there should be an anisotropic distribution of trap energy states available, as well as a distribution in the concentration of those states. Fig. 2 lends electronic evidence to the inferences of the visual evidence of TEM [24]. For the 0.3 dpa and 0.5 dpa samples, it is no longer the junction capacitance (which is frequency independent and is not lifetime sensitive) that dominates in the silicon, but diffusion capacitance or charging due to traps, which are frequency dependent [40]. The junction capacitance is associated with oscillations in the depletion width due to small sinusoidal perturbations [41]. The diffusion capacitance is associated with minority carriers and changes in change due to the sinusoidal perturbation signal. Because there is a distribution of trap and acceptor states within the irradiated silicon, the diffusion capacitance will not be a constant, but will itself be a function of frequency, and change the relationship between the complex impedance and frequency.

The equivalent series resistance of the device is dominated by the bulk resistivity of the silicon substrate. The range of this value is easily calculated. Resistance of a thin film is defined by the equation:

$$ R = \frac{\rho L}{w t} \quad (3) $$

where ρ is the film resistivity, L is the length of the surface, w is the width of the surface (consider L the longer of the two values), and t is the film thickness perpendicular to the surface. Though dimensionless, the ratio L/W is taken as the number of squares through which charge carriers must traverse. A 380 μm thick substrate, with a 2 mm diameter contact (approximating L/W = 1 square) and resistivity between 1 and 10 Ω·cm results in a resistance between 26 and 260 Ω. As previously stated, the equivalent series resistance parameter R3 does not deviate from this range, and changes in R3 are not considered to be a result.
of irradiation, but rather small changes in carrier concentration within the silicon substrate, or small changes in device preparation.

R1 is the variable that undergoes the most drastic change. According to Nordell et al. [50], the resistivity of a-B_{10}C_{2+x}:H_y films ranges from 10^{10} to 10^{15} \Omega \cdot \text{cm}. A 200 nm thick film with a 2 mm diameter metal contact (approximating L/W = 1 square) would result in a resistance on the magnitude of 10^{16} \Omega. 11 orders of magnitude greater than any resistance values obtained in Table 1. However, if the film is completely depleted of charge carriers, and only acting as a dielectric between 2 parallel plate contacts with a significant barrier at the silicon interface due to the heterojunction band misalignment, the values of R1 for the virgin and 0.1 dpa measurements can be explained.

First, it has yet to be shown what metals makes an ohmic contact with a-B_{10}C_{2+x}:H_y films. It is possible a metal with a higher work function than chromium is required. This suggests that there could be a contact resistance at the device cathode in the form of a Schottky barrier. However, since the Schottky barrier is a majority carrier process, the barrier is frequency independent, and will only change as a result of chemical or structural changes in the film. The band misalignment between the a-B_{10}C_{2+x}:H_y film and the silicon provides a frequency dependent junction resistance that will change as a result of changes in the charge carrier concentrations of either the film or the silicon.

Examining the virgin measurement, we first make the approximation from the indicated parallel resistance of 6082 \Omega, that the a-B_{10}C_{2+x}:H_y film is fully depleted. Were this not the case, our calculation above shows that this value or the equivalent series resistance (R3) would be many orders of magnitude larger. This leads to the interpretation of this value as the junction resistance due to barriers within the band structure.

Examining the 0.1 dpa measurement, the second parallel R2 component has an indicated junction resistance of 40 \Omega [53]. Type inverted silicon as a result of neutron radiation reaches an upper limit asymptote of resistivity at approximately 2.4 \times 10^5 \Omega \cdot \text{cm} [51]. This is a direct result of the damage to the crystalline Si substrate. In order for the Si dopant to contribute to the conductivity of the Si, the substitutional atom (i.e. P) must sit on a Si lattice site. If the dopant is disturbed, and becomes an interstitial defect as a result of radiation damage, it is no longer active, and will not contribute to the conductivity. Prior to the damage clusters created near the ion end of range, the irradiating ion is creating point defects in the Si all along its ion track. These point defects reduce the average carrier relaxation time and de-activate the dopants, both of which increase the resistivity of the Si.

From equation (3), an ion range of 1400 nm and a contact area again of 2 mm diameter (approximating L/W = 1) would result in a resistance in the irradiated silicon of approximately 1.71 \times 10^9 \Omega. However, as before this calculation assumes no depletion region, which is inaccurate. There will be a depletion region at the p p^- junction with the a-B_{10}C_{2+x}:H_y/Si(irradiated), and at the p^-n homojunction between the Si(irradiated)/Si(virgin). Since neither the exact carrier concentration or change in band structure is known for the a-B_{10}C_{2+x}:H_y film, the depletion widths at this junction are not accurately calculable. However, a rough estimate of the depletion width resulting from the p^-n homojunction shows the irradiated silicon and a-B_{10}C_{2+x}:H_y film being fully depleted. Just as with the examination of the a-B_{10}C_{2+x}:H_y film, a resistance on this order of magnitude is not found in the 0.1 dpa model, and lends support to the full depletion approximation.

Croitoru et al. [51] provide resistivity and mobility measurements of irradiated silicon, allowing for the calculation of the hole carrier concentration for the case N_A >> N_D through:

$$\rho = \frac{1}{\pi \mu_p N_A}$$  \hspace{1cm} (4)

where \(\rho\) is resistivity, \(q\) is the elementary charge, \(\mu_p\) is the hole hall mobility, and \(N_A\) is the acceptor concentration. Taking the values from Croitoru’s highest measured fluences (10^{16} n/cm^2) of \(\rho = 234280 \Omega \cdot \text{cm}\) and \(\mu_p = 70 \text{ cm}^2/\text{Vs}\), we calculate \(N_A = 3.8 \times 10^{11} \text{ cm}^{-2}\). The carrier concentration of the virgin silicon substrate is estimated at \(N_D = 1 \times 10^{15} \text{ cm}^{-2}\) (based on the manufacturer’s specifications). This leads to an estimate of the silicon homojunction depletion width (\(w\)) of 36 \mu m:

$$w = \left(\frac{2k_B T}{q} \frac{N_A + N_D}{N_A - N_D}\right)^{1/2}$$  \hspace{1cm} (5)

$$V_{bl} = \frac{k T}{q} \ln \left(\frac{N_A N_D}{n_i^2}\right)$$  \hspace{1cm} (6)

where \(k\) is the dielectric constant, \(\varepsilon_0\) is the permeability of free space, \(N_A\) is the number of acceptors, \(N_D\) is the number of donors, \(V_{bl}\) is the built in voltage, \(n_i\) is the intrinsic carrier concentration, \(k\) is the Boltzmann constant, \(T\) is temperature. Considering that the ion range is only 1.4 \mu m, and the a-B_{10}C_{2+x}:H_y film is only 225 nm thick, we can safely assume that the type-inverted silicon and a-B_{10}C_{2+x}:H_y film are fully depleted.

Of much more importance in the 0.1 dpa data, is the decrease of R1 from 6028 to 2782 \Omega. Using the approximation that the film is fully depleted of charge carriers, and the band alignment of the a-B_{10}C_{2+x}:H_y film to type inverted silicon is considered, the barrier of a p p^- heterojunction will be much smaller than that of a p-n heterojunction even if the constituent band gaps are altered as a result of the irradiation. As an example to prove this point, let us assume the HOMO – LUMO gap of a-B_{10}C_{2+x}:H_y is 2.0 eV (values of 0.7 to 3.8 eV have been reported [40]). It has been shown that the acceptor and trap energy levels of type-inverted silicon are mid-band gap [55], so let us further assume that the band gap of the silicon is not significantly altered from 1.12 eV. The conduction band barrier of the a-B_{10}C_{2+x}:H_y/virgin silicon p-n heterojunction is roughly 2.0 eV – (E_T + E_N) – (E_F + E_D) \approx 2.0 eV. Through band realignment of a type-inverted silicon region, the p^- conduction band barrier will be roughly 2.0 eV – 1.12 eV \approx 0.88 eV. Such a reduction in the barrier height would be reflected in the parallel junction resistance component of our equivalent circuit model. Our example shows a reduction of roughly 1/2 in barrier height, which compares to our R1 results in Table 1.

Examination of the 0.2, 0.3, and 0.5 dpa measurements shows a dramatic increase in the resistance parameter R1 from 2782 to
190000 Ω. Maintaining the assumption that this remains a combination of the junction and contact resistances, one explanation for the dramatic increase of parameter R1 is further heterojunction band modification and/or Schottky barrier modification. This modification could be additional band realignment due to defect passivation resulting in a decrease in N_A and a shift from a p-type to an intrinsic semiconductor and simultaneously reducing the concentration of recombination/generation centers within the HOMO – LUMO gap. Another possibility is a direct change in the a-B_{10}C_{2+x}:H_y film, as it has been shown that new mid-band gap vacancy complexes are forming in the silicon [43-49].

While this paper presents a possible explanation for the initial increase in heterojunction device performance under irradiation, it is still not entirely clear to what extent the a-B_{10}C_{2+x}:H_y film is chemically or structurally modified by the irradiating ions. A more direct means of investigating the a-B_{10}C_{2+x}:H_y film is required. Future experiments seek to examine a-B_{10}C_{2+x}:H_y films as a lossy capacitor in a metal oxide semiconductor system (C-MOS). This will allow for the elimination of the issues created by the changing silicon substrate and exclusively examine the charge carriers of the a-B_{10}C_{2+x}:H_y film.

V. CONCLUSIONS

In conclusion, a-B_{10}C_{2+x}:H_y on Si p-n heterojunctions were synthesized utilizing PECVD. Following irradiation with 200 keV He^+ ions, the heterojunction properties were explored through electrical characterization. A model has been presented for calculating conductance as a function of frequency for semiconductors under irradiation. This model was then used to interpret measured data and infer physical and chemical changes in the device.

For low doses of irradiation, the resistance of the R1 component decreased. This is most likely due to band realignment of the a-B_{10}C_{2+x}:H_y/Si heterojunction as the irradiated silicon type-inverts creating a p-p^+ heterojunction and reducing the barrier height. Simultaneously, the crystalline Si substrate is being damaged. Point defects are decreasing the average carrier relaxation time, and dopants are being deactivated, resulting in an increase in the resistivity of the Si. For moderate doses of irradiation, it is believed that the electronic energy deposition from the irradiating ions may be perturbing the atoms within the a-B_{10}C_{2+x}:H_y film allowing for the elimination of defects, and decreasing the hole concentration (N_A). Even though the a-B_{10}C_{2+x}:H_y film is fully depleted of charge carriers, changes to the defect concentration (i.e. concentration of generation/recombination centers), and hole concentration (N_A) will change the Fermi energy (E_F) location within the HOMO-LUMO gap. This in turn causes band realignment, and would change the energy barrier at the a-B_{10}C_{2+x}:H_y/Si junction. Therefore, if the a-B_{10}C_{2+x}:H_y film has been altered to have less recombination/generation centers and/or smaller N_A the a-B_{10}C_{2+x}:H_y/Si junction resistance will increase, explaining the results of R1 in table 1.

APPENDIX A

Recognizing that the complex impedance of a resistor and capacitor in parallel is

\[ Z_{R1C1} = \frac{R1(f\omega C1)^{-1}}{R1+(f\omega C1)^{-1}} \]  

(B.1)

The equivalent complex impedance of the circuit in Fig. 1 is

\[ Z_{eq} = -\frac{R1 f}{C1 \omega (R1-\frac{1}{C1 \omega})} - \frac{R2 f}{C2 \omega (R2-\frac{1}{C2 \omega})} + R3 \]  

(B.2)

The complex admittance (Y) is the reciprocal of the complex impedance

\[ Y = \frac{1}{Z_{eq}} = \left(\frac{R1 f}{C1 R1 \omega^2} + \frac{-1}{C2 R2 \omega^2} + R3\right) \]  

(B.3)

The conductance of a device is the real part of the complex admittance. To obtain the real component of Y, normalize the
equation

\[ Y = \frac{-\left( C_1 R_1 \omega - j \right) \left( C_2 R_2 \omega - j \right)}{\left[ (R_1 + R_2 + R_3 + (C_2 R_2 R_3 \omega j) + (C_2 R_1 R_2 \omega j) - (C_1 C_2 R_1 R_2 R_3 \omega^2) + (C_1 R_1 R_2 \omega j) + (C_1 R_1 R_3 \omega j) \right]} \]  

(B.4)

Multiply by the complex conjugate

\[ Y = \frac{-\left( C_1 C_2 R_1 R_2 \omega^2 \right) \sigma_1 + \left( C_1 R_1 \omega + C_2 R_2 \omega \right) \sigma_2}{\sigma_1 + \left( C_1 C_2 R_1 R_2 \omega^2 \right) \sigma_2} \]  

(B.5)

where

\[ \sigma_1 = \sigma_2^2 + \sigma_3^2 \]
\[ \sigma_2 = C_1 R_1 R_3 \omega + C_2 R_2 R_3 \omega + C_1 R_1 R_2 \omega + R_1 R_2 C_2 \omega \]
\[ \sigma_3 = R_1 + R_2 + R_3 - C_1 R_1 C_2 R_2 R_3 \omega^2 \]

Taking the real part of equation (B.5) gives the equation modeling the measured conductance

\[ G_m = \frac{\omega^2 \left( C_1 C_2 R_1 R_2 + C_2 R_2 R_3 \right) \left( C_1 R_1 + C_2 R_2 \right) + \left( C_1 R_1 + C_2 R_2 \right) \omega^2}{\sigma_4 \left( C_1 C_2 R_1 R_2 \omega^2 \right) \left( -C_1 C_2 R_1 R_2 \omega^2 \right) + \left( R_1 + R_2 + R_3 \right) \omega^2} \]  

(B.6)

where

\[ \sigma_4 = \left( C_1 R_1 R_3 \omega + C_2 R_2 R_3 \omega + C_1 R_1 R_2 \omega + C_2 R_1 R_2 \omega \right)^2 \]
\[ + \left( R_1 + R_2 + R_3 \right)^2 \]

APPENDIX C

When a \(^{10}\)B atom captures a neutron, a \(^{11}\)B compound nucleus forms which fragments into \(^7\)Li and an alpha particle with large translational energy, and \(94\%\) of the time, gamma radiation. This is represented below [1, 10, 34].

\[^{10}\text{B} + n \rightarrow ^7\text{Li} (0.84 \text{ MeV}) + ^4\text{He} (1.47 \text{ MeV}) + \gamma (0.48 \text{ MeV}) \]
(94\%)

\[^{10}\text{B} + n \rightarrow ^7\text{Li} (1.02 \text{ MeV}) + ^4\text{He} (1.78 \text{ MeV}) \]
(6\%)

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