Compensating defect in deep buried layers produced by MeV heavy ions in *n*-silicon

P. K. Giri and Y. N. Mohapatra
Department of Physics, Indian Institute of Technology, Kanpur 208016, India

(Received 9 June 1997; accepted for publication 19 July 1997)

Buried damaged layers in *n*-silicon created by implantation of MeV heavy ions (Ar^+) have been studied by capacitance and current measurements, and spectroscopic techniques such as deep level transient spectroscopy and constant capacitance time analyzed transient spectroscopy. We have isolated a new midgap acceptor level responsible for carrier compensation in samples irradiated with doses below amorphization threshold. This defect level is demonstrated to control hysteresis in capacitance-voltage characteristics, space charge limited current conduction, and premature termination of emission transients. The emission energy of the defect is observed to be sensitive to degree of disorder in the damaged layer controlled by irradiation dose, and relaxation induced by heat treatment. © *1997 American Institute of Physics.* [S0003-6951(97)02938-0]

The use of deep buried layers in silicon produced by MeV heavy ion implantation has emerged as an increasingly important tool in the design of device structure for introduction of dopants, control of lifetime and composition, production of amorphous layers prior to solid phase epitaxial growth, etc.[1,2] It is also known that defects produced in as-implanted layers control subsequent evolution of defects and extent of relaxation of the disordered layer.[3] Hence a knowledge of physics of defect process in the buried layer has become a significant concern. Though a variety of structural tools have been used to study such layers,[4] electrical characterization has often been limited to conductivity measurements.[5] This is mainly due to lack of convenient test device structure, and limitations in use of conventional defect spectroscopic techniques to study these layers. For example, though it is widely known that MeV implantation damage creates carrier compensation, the nature, role, and influence of defects responsible for this is little understood.

In this letter, we report the study of defects in deep buried, damaged layers produced by MeV heavy ion implantation in *n*-Si. We have isolated the defect primarily responsible for compensation in the damaged region. It is shown that the defect manifests itself through several interesting and unusual features in capacitance-voltage (C-V), current-voltage (I-V) characteristics of Schottky diode containing the damaged layer, as also in conventional deep level transient spectroscopy (DLTS) and constant capacitance (CC) time analyzed transient spectroscopy (TATS).[6]

Samples used for this study were phosphorus doped epitaxial silicon wafers of resistivity 2–5 Ω cm on n^+ substrate. These wafers were irradiated from front side at room temperature with 1.45 MeV Ar^+ ion (having an approximate mean range of 1.23 μm) using a 2 MeV Van de Graaff accelerator. Ion doses of 5×10^{13} cm^{-2} and 1×10^{14} cm^{-2}, which are just below amorphization threshold, were used to create damage. Schottky diodes were formed with evaporated gold dots on irradiated wafers. The diodes receiving only the heat treatment of 70 °C for 30 minutes for curing epoxy contacts will be referred to as as-implanted samples. Some mounted devices were oven annealed at a relatively low temperature of 160 °C for 30 minutes. Capacitance measurements were carried out using Boonton capacitance meter (Model 72B) operated at 1 MHz. The transient data were analyzed using conventional DLTS and CC-TATS. The first order CC-TATS signal[6] is given by $S(t)=V(t)-V(t+\gamma t)$, where γ is an experimentally selectable constant and $V(t)$ is voltage transient in constant capacitance mode. TATS line-shape analysis has been exploited to evaluate the nature of the transients associated with defect phenomena.

Figure 1(a) shows a typical capacitance response on application of a voltage pulse (from reverse bias of −4 V to 0 V, for a filling time of t_f) to a Schottky diode which has the damaged region embedded in the depletion layer. Note the occurrence of a sharp capacitance spike during filling pulse. On reapplication of the reverse bias voltage (V_R) a very large magnitude of capacitance transient results even though the net change in capacitance at the end of filling pulse is very small. This indicates that the spike is due to filling of large number of traps forcing the depletion layer to widen during the zero bias pulse. From a closer look at the transient, it is apparent that the steady state is achieved rather

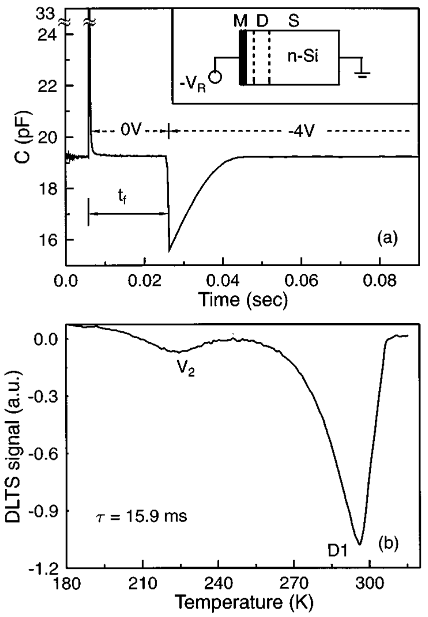

FIG. 1. (a) A typical capacitance response on application of a voltage pulse (from −4 V to 0 V, for time t_f) to ion damaged Schottky device at 293.3 K. Inset shows the schematic of device structure showing metal (M), damaged region (D) and undamaged silicon region (S). (b) A typical DLTS spectrum of the irradiated *n*-Si showing two peaks (V_2, D1).

0003-6951/97/71(12)/1682/3/$10.00

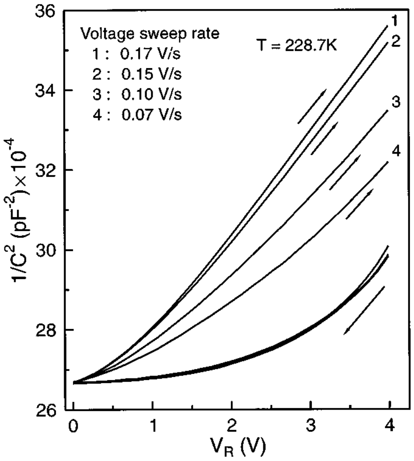

FIG. 2. $1/C^2$ vs V_R plot showing hysteresis for decreasing and increasing reverse bias with different voltage sweep rates.

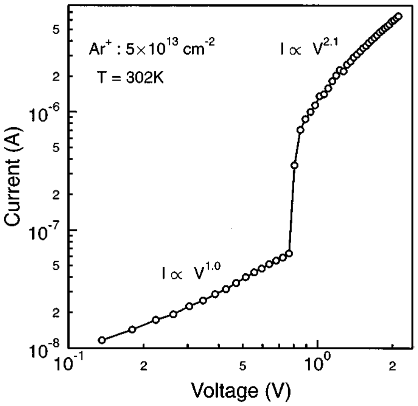

FIG. 3. Forward I-V characteristics of Schottky diode containing the damaged layer showing ohmic and space charge limited current conduction regimes at 302 K.

suddenly and prematurely before the characteristic time that the transient ought to have taken to decay. Figure 1(b) shows a typical DLTS spectrum for such a sample where two peaks are observed in the temperature range 90–320 K. Peak labelled V_2 is due to the second ionization of the well known divacancy center at energy $E_c - 0.42$ eV with capture cross-section of 3×10^{-15} cm^2.[7] Peak labelled as D1 is a newly found level which occurs consistently in large concentration in our samples implanted with high doses. An unusual feature in the DLTS lineshape of D1 is the sharp rise in the curve at right side of the peak corresponding to premature end to the transient shown in Fig. 1(a). As the cusp like peak is not the true peak in DLTS, and since large concentration of defects are involved, a conventional analysis to obtain trap parameter for defect D1 is not appropriate here.

Figure 2 shows the dependence of $1/C^2$ versus V_R plots on direction and rate of voltage sweep demonstrating occurrence of hysteresis. This is clearly due to large concentration of D1 centers since the sweep rates are comparable to the emission rate of this level at this temperature. The C-V characteristic is identical for different sweep rates when the voltage is decreased owing to fast capture process at the traps, while it is different on increasing the voltage since it is now controlled by rate of emission. The zero bias depletion width of most devices having damaged layer are 2-3 μm larger than their corresponding control devices. Also note that the depletion width is larger when the reverse bias is increased after allowing capture during C-V measurements indicating that defect D1 captures majority electrons and hence act as the dominant compensating center in the damaged layer. This is also consistent with the existence of large capacitance spike during filling pulse as described in Fig. 1(a). After the capture of electrons, the negatively charged D1 defects are so large in number that the depletion region is pushed back to uncover required amount of positive fixed charge in the undamaged portion to maintain charge balance condition. As the damaged region embedded within the depletion layer is a compensated layer owing to deep level defects D1, the electrical characteristics is dominated by a ‘‘junction’’ between the defect controlled compensated layer and the virgin n-type layer beyond the damaged layer. Our estimates show that the defect is present in concentration comparable to background doping at distances much larger than the range of the ions as predicted by TRIM simulations.[8]

The fact that the damaged layer acts as a defect controlled near-intrinsic region can be seen from forward I-V measurements on the same diode. A typical forward I-V characteristic curve is shown in Fig. 3 which display a near ideal case of crossover from ohmic conduction to square law space charge limited conduction regime at the voltage corresponding to trap filled limit (V_{TFL}). The nearly vertical rise in current accompanying the trap filling is an indicator that the associated defect is a discrete level.[9] In this case, it must be due to the dominant defect D1 which controls hysteresis in C-V and is also observed in large concentration in DLTS spectra. Hence the structure under study is akin to a p-i-n diode, where p is replaced by a metal and i-region is nearly intrinsic due to presence of D1 in the damaged region.

In order to obtain reliable information regarding the defect D1, an isothermal spectroscopic technique such as CC-TATS is necessary. CC-TATS spectra corresponding to defect D1 is shown in Fig. 4 as solid lines for two samples, one as-implanted and the other heat treated at 160 °C. The dotted line in each case show the simulated TATS spectra with exponential transient treating the apparent peak as the true peak, while in contrast the broken line in each case correspond to an exponential transient only considering the portion prior to the peak. Since we know that the apparent peak is only an artefact of premature termination of the transient as already seen in DLTS spectrum (Fig. 1), it is only the latter fitting by broken lines that is meaningful.

However, questions can be raised regarding uniqueness of such a fit where both peak height and time constant are treated as free parameters in the fitting process. In order to test for the exponential character of the portion of the signal prior to the apparent peak, we resort to a method of point by point analysis of the transient to evaluate time constant as described by Mangelsdorf.[10] We indeed find that within experimental errors a single time constant is involved till the time of the sudden termination of the transient. The parameters so obtained show that time constant obtained from apparent peak position and peak amplitude are both underestimates. The energy level and capture cross-section obtained from four sets of samples for combinations of dose and an-

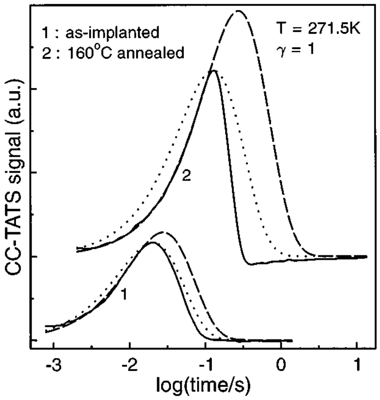

FIG. 4. CC-TATS spectra corresponding to defect D1 for Ar^+ ion dose of 5×10^{13} cm^{-2}. In each case, solid line corresponds to experimental data, dotted line shows simulated TATS spectra treating the apparent peak as true peak, while the broken line corresponds to exponential transient only considering the portion prior to the peak.

nealing conditions are shown in Table I. The energy level of the defect D1 is seen to vary between 0.49 eV to 0.56 eV below conduction band depending on processing conditions. The magnitudes of capture cross-section is typical of a deep neutral center. The variation in emission energy can be attributed to the defect's sensitivity to the degree of disorder in its environment or the degree of relaxation in the damaged layer. For both annealed and lower dose implanted samples, the energy is deeper indicating that the defect is in more relaxed configuration. The degree of filling seems to increase for the relaxed material showing larger peak height in DLTS or CC-TATS.

The occurrence of sudden cessation of the emission transient leading to premature termination of peak in DLTS and CC-TATS spectra can be understood as follows. On restoration of reverse bias immediately after the filling pulse, the depletion width increases considerably owing to large increase in negative charge in the damaged layer, thus pushing the Fermi level down below the trap level in the damaged region. This leads to exponential emission of carrier from extra trapped charge till the quasi-Fermi level hits the trap level quickly bringing emission transient to an end. Note that the phenomena is crucially dependent on the fact that the emitting center itself controls the quasi-Fermi level in the damaged region and the overall band bending through its occupancy. Hence, in general premature termination is to be expected in a p-i-n like structure where the intrinsic i-region is compensated due to a deep level. Observations of similar sudden termination of transients have been reported earlier in electron irradiated material and ascribed to reasons such as entropy driven metastability[11] or recombination currents.[12] In our opinion, mechanisms responsible for anomalous phenomena such as these are best understood when studied in the time domain using isothermal transient spectroscopies.

TABLE I. Trap parameters for the major peak (D1).

	as-implanted		160 °C annealed	
Ar^+ Dose (cm^{-2})	E_c-E_T (eV)	σ_n (cm^2)	E_c-E_T (eV)	σ_n (cm^2)
5×10^{13}	0.54	2.4×10^{-15}	0.56	7.4×10^{-16}
1×10^{14}	0.49	7.7×10^{-16}	0.52	1.1×10^{-15}

It is tempting to attribute defect D1 to either dangling bonds (D-centers) or higher order complexes of intrinsic defects.[13] Recently it has been shown from molecular dynamic simulations and high resolution electron microscopy observations that accumulation of di-interstitial (D-D) pairs occurs in heavy ion implanted layers leading to homogeneous amorphization beyond a threshold dose.[4] Furthermore, Privitera *et al.*[14] have recently demonstrated long range room temperature migration of Si self-interstitials. Since we have observed the major defect (D1) to be lying much beyond the TRIM predicted profile, there is a strong indication of possible involvement of interstitial complex such as di-interstitial. Photocarrier lifetime measurements in ion-implanted a-Si have shown presence of midgap states with capture cross-section $\sigma_n\sim6\times10^{-16}$ cm^2 (Ref. 13) which is similar to the observed values in this work. The significance of defect D1 also lies in the observation that it is sensitive to strain and disorder in the environment and hence can act as a probe in the study of degree of disorder for high dose implantations. It would be interesting to investigate the role of accumulation of D1 defects for higher doses in creation, relaxation, and eventual regrowth of such layers.

In conclusion, we have isolated a defect responsible for carrier compensation in the damaged region produced by high dose implantation of Ar^+ ions in n-Si. It is shown to give rise to unusual and interesting features such as hysteresis in C-V characteristics, capacitance spike during filling pulse, trap filled limit space charge conduction, and sudden termination of emission transients. The trap energy lies deeper in the band gap for lower dose and for temperature induced relaxation of the damaged layer showing its sensitivity to the environment.

The authors are grateful to Dr. V. N. Kulkarni and Dr. Sankar Dhar for valuable help in ion irradiation and sample preparation.

[1] J. S. Williams, R. G. Elliman, M. C. Ridgway, C. Jagadish, S. L. Ellingboe, R. Goldberg, M. Petravic, W. C. Wong, Z. Dezhang, E. Nygren, and B. G. Svensson, Nucl. Instrum. Methods Phys. Res. B **80/81**, 507 (1993).

[2] J. O. Borland and R. Koelsch, Solid State Technol. **36**, 28 (1993).

[3] S. Roorda, W. C. Sinke, J. M. Poate, D. C. Jacobson, S. Dierker, B. S. Dennis, D. J. Eagleshman, F. Spaepen, and P. Fuoss, Phys. Rev. B **44**, 3702 (1991).

[4] T. Motooka, S. Harada, and M. Ishimaru, Phys. Rev. Lett. **78**, 2980 (1997).

[5] S. Coffa, F. Priolo, and A. Battaglia, Phys. Rev. Lett. **70**, 3756 (1993).

[6] S. Agarwal, Y. N. Mohapatra, and V. A. Singh, J. Appl. Phys. **77**, 3155 (1995).

[7] B. G. Svensson, M. Mohadjeri, A. Hallen, J. H. Svensson, and J. W. Corbett, Phys. Rev. B **43**, 2292 (1991).

[8] J. F. Zeigler, J. P. Biersak, and U. Littmark, *Stopping of Ions in Solids* (Pergamon, New York, 1985).

[9] M. A. Lampert and P. Mark, *Current Injection in Solids* (Academic, New York, 1970), Chaps. 2, 4.

[10] P. C. Mangelsdorf, Jr., J. Appl. Phys. **30**, 442 (1959).

[11] B. Hamilton, A. R. Peaker, and S. T. Pantelides, Phys. Rev. Lett. **61**, 1627 (1988).

[12] M. Zazoui, J. C. Bourgoin, D. Stievenard, D. Deresmes, and G. Strobl, J. Appl. Phys. **76**, 815 (1994).

[13] P. A. Stolk, F. W. Saris, A. J. M. Bernsten, W. F. van der Weg, L. T. Sealy, R. C. Barklie, G. Krotz, and G. Muller, J. Appl. Phys. **75**, 7266 (1994).

[14] V. Privitera, S. Coffa, F. Priolo, K. K. Larsen, and G. Mannino, Appl. Phys. Lett. **68**, 3422 (1996).