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Characterization of deep level defects in Si irradiated with MeV Ar^+ ions using constant capacitance time analyzed transient spectroscopy

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Abstract. An isothermal spectroscopic technique called time analyzed transient spectroscopy (TATS) in the constant capacitance (CC) mode has been used to characterize electrically active defects in the MeV Ar^+ implanted silicon. The problems associated with high defect density and the presence of damaged region in the as-implanted material are overcome by CC-TATS method. The CC-TATS spectra of the as-implanted sample shows two positive peaks and an attendant negative peak. Two distinct traps have also been identified using thermally stimulated capacitance method modified to operate in constant capacitance mode. Variable pulse width measurements using CC-TATS show exponential capture kinetics in contrast to extremely slow capture observed in conventional deep level transient spectroscopy (DLTS) experiment. The results indicate that trapping behaviour is due to point-like defects associated with extended defects such as dislocation and stacking fault.

Keywords. Defects; ion implantation; deep level transient spectroscopy.

1. Introduction

The effect of high energy heavy ion implantation in semiconductors is being investigated extensively at present due to its potential applications in tailoring material properties and device structures. Production of deep buried layers with controlled damage and doping, and control of lifetime of carriers has been made possible using heavy ion implantation. The suitability of high energy implantation rests on a thorough understanding of dynamics of electrically active defects induced by implantation and their subsequent annealing. However, there are several problems associated with the meaningful electrical characterization of deep level defects in as-implanted semiconductors. Principal among them is the effect of a physically disordered region which makes standard use of depletion layer spectroscopy such as deep level transient spectroscopy (DLTS) invalid. Identification and characterization of deep level defects in unannealed samples are becoming increasingly important in view of the need to understand defect creation mechanisms and dependence of defect dynamics on processing parameters.

Large concentration of traps and the presence of series resistance in the device gives rise to distorted transients. Such nonexponentialities in capacitance transient under constant bias can be avoided by performing the transient analysis on the voltage transient in constant capacitance mode (Miller 1972). In this method, the capacitance is held constant during carrier emission measurement by dynamically varying the applied voltage during the transient response through feedback circuit.

In this work, we study deep level defects induced by high energy heavy ions in silicon using conventional DLTS and show that time analyzed transient spectroscopy (TATS) (Agarwal *et al* 1995) in the constant capacitance (CC) mode is a more reliable method to characterize electrically active defects in as-implanted silicon. The problems associated

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with characterization in the presence of resistive damaged region and high defect densities in the as-implanted material are overcome by CC-TATS method. The CC-TATS spectra of the as-implanted sample show two positive peaks and an attendant negative peak. Two distinct traps have also been identified using thermally stimulated capacitance (TSCAP) modified to operate in CC mode. Capture behaviour of these traps have been assessed using varying pulse width technique. Critical comparison with results existing in the literature of conventional DLTS characterization on plastically deformed silicon is presented.

2. Experimental

Polished p-type silicon wafers of 4–7 Ωcm resistivity, (111)-orientation was used for making Schottky contact with vacuum deposited aluminium. Control diodes tested by $C-V$ measurement showed uniformity of shallow doping. $I-V$ measurements were done to check the quality of the diode. The implantations were performed at room temperature with 1·5 MeV Ar^+ ions for doses of 1×10^{14} and 5×10^{14} ions/cm^2 on the finished device from the front side of the device. No post-implantation annealing was done on any of the samples. A Boonton capacitance meter (72B) operated at 1 MHz was used for capacitance transient measurements. The whole set up is computer (PC) controlled except for temperature control.

3. Results and discussion

The control sample is tested for any trap level signature using conventional DLTS. No traps could be detected up to detection limit of 10^{-3} of the background doping in the unirradiated samples. A typical DLTS spectrum obtained after an irradiation fluence of 1×10^{14} Ar^+ cm^{-2} is shown in figure 1. A steady state reverse bias of 4·5 V has been applied before cooling down to liquid nitrogen temperature. The pulse height was $\Delta V = 4·4$ V. One major peak along with two small peaks are observed. Note that

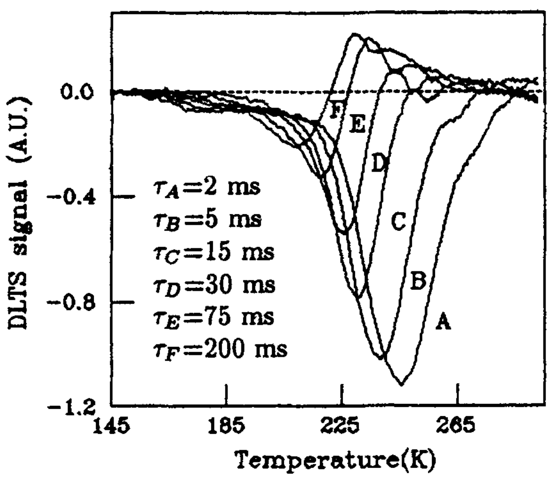

Figure 1. DLTS spectra of Si irradiated with Ar^+ at dose 1×10^{14} cm^{-2} showing negative peak for slower rate windows.

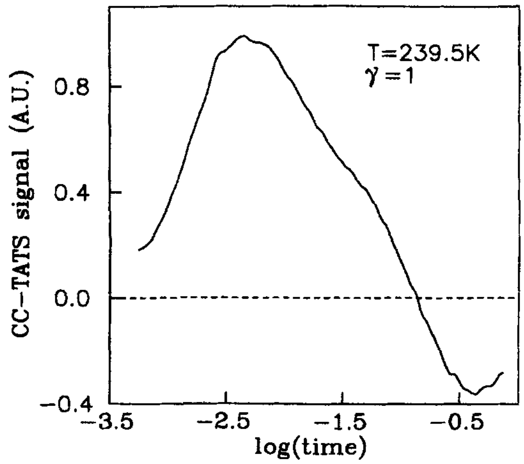

Figure 2. CC-TATS spectra of the same sample showing two positive peaks and attendant negative peak.

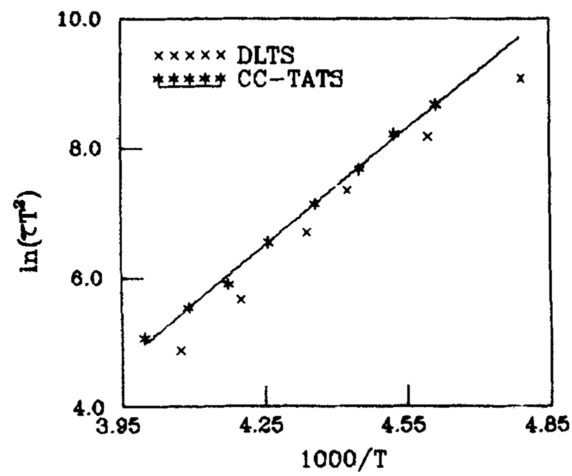

Figure 3. Arrhenius plot for the major peak in CC-TATS and DLTS spectra.

for smaller rate windows DLTS peak height goes down and it becomes negative for $\tau > 15$ ms. Sign reversal of the DLTS peak due to presence of series resistance is well known (Broniatowski *et al* 1983).

It can also be theoretically shown that due to presence of series resistance DLTS peak width narrows down and peak shifts in temperature (Giri and Mohapatra, unpublished). For a dynamically variable series resistance in device, the analysis is extremely difficult. As the capacitance change is large in this case, use of conventional (constant voltage) DLTS technique gives rise to a nonlinear Arrhenius plot (cf. figure 3, cross symbols).

To avoid the problems of varying series resistance, TATS has been used in the constant capacitance mode. Recently we have used this isothermal spectroscopic method to study nonexponentiality of transients and shown its advantages over traditional DLTS analysis for other standard defects in GaAlAs and GaAs (Giri and

Mohapatra 1995). TATS spectra for the as-implanted sample is shown in figure 2. Along with the major peak, a small positive peak and a negative peak is seen. In this case filling pulse was applied for 1 sec to ensure complete filling of the traps. The peak heights are similar for different temperature transients. Arrhenius plot shown in figure 3 for the major peak gives an activation energy of 0·52 eV which is a midgap acceptor level. In light ion irradiated Si, this defect is not seen. But similar defects have been identified in heavy ion implanted Si and it has been attributed to damage related level (Krynicki *et al* 1989). Two peaks have been observed in the same sample using TSCAP modified to operate in constant capacitance mode. No negative peak signature is found from CC-TSCAP measurement.

The dominant peak in TATS spectra is broader than the corresponding exponential transient. Occurrence of broadening in TATS spectra can be attributed to the spread of activation energies in the presence of dislocations (Woodham and Borrker 1987). Since, such deep levels would experience different strain field as in the case of less perfect crystals, the model for broadened deep energy levels would be applicable. For Gaussian distribution of energy, using the input parameters such as temperature, apparent activation energy and capture cross section deduced from Arrhenius plot of time constants obtained from isothermal transient spectroscopy, the observed major peak could be fitted with full width half maxima (FWHM) of 30 meV. Similar results have been obtained for deep levels found in plastically deformed silicon (Omling *et al* 1985; Kisielowski and Weber 1991). Occurrence of the negative peak in CC-TATS spectra is not due to the damaged layer created by Ar^+ ion since high dc resistance does not distort transients in CC mode of operation. Moreover, measurements completely away from the damaged region also show such negative peak. This feature seems to be characteristic of *p*-Si samples irradiated with heavy ions. Similar studies on *n*-Si does not show such negative peak.

Capture cross-section estimated from the intercept of Arrhenius plot is $9{\cdot}9 \times 10^{-13}\,cm^2$. Figure 4 shows filling time dependence of occupation of the major trap at 230·4 K using constant capacitance varying pulse width technique. Capture is seen to be fairly exponential which is expected from point defect nature of the traps.

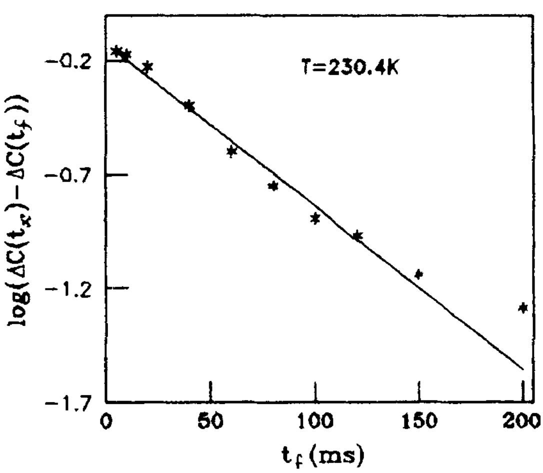

Figure 4. Filling time dependence of the occupation of observed major trap in as-implanted Si.

However, for the same sample, using constant voltage transients, trap occupation during capture is observed to be slow and approximately logarithmic in time. Hence, we conclude that such slow filling is an artefact of nonexponentiality due to large trap concentration. Logarithmic time dependence of capture has been reported for plastically deformed silicon with dislocation from conventional DLTS measurement (Kveder *et al* 1982; Omling *et al* 1985; Kisielowski and Weber 1991) and time dependent capture has been invoked to explain the results. Our CC-TATS results show that the reported logarithmic filling time behaviour may be based on questionable experimental methodology for these materials. Temperature dependent capture behaviour is seen in our sample for the observed major trap which is characterized by high capture barrier. The observed capture barrier is most probably due to Coulomb repulsive barrier seen by holes captured at charged extended defects. Since the structural defects themselves do not show any electrical signature, the observed trapping behaviour is indicative of point defects associated with dislocations. More detailed study on capture kinetics is under investigation.

4. Conclusions

In summary, we have shown that constant capacitance TATS should be the preferred method of characterization of deep levels in presence of high resistive damaged layers. It has been used to characterize deep level defects in MeV Ar^+ ion implanted Si. As-implanted samples show two peaks of which the major peak has been ascribed to point defects associated with dislocation. The origin of the negative peak is not clear to us. Temperature dependent capture behaviour of the traps and broadened TATS spectra indicate the involvement of extended defects decorated with point defects.

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