

SENSITIVITY OF ELECTRICALLY ACTIVE DEFECT SPECTRA TO PROCESSING CONDITIONS IN MeV HEAVY ION IMPLANTED SILICON

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ABSTRACT

We have carried out electrical characterization of defects in heavily damaged silicon, where damage is created by MeV heavy ions at doses near but below amorphization threshold and samples are subjected to different annealing conditions. Defect characterization is carried out using combination of deep level transient spectroscopy (DLTS) and isothermal time analyzed spectroscopy (TATS). The defect spectrum is observed to be sensitive to i) furnace annealing between 400-600 °C, ii) low temperature oven annealing at 160 °C, and iii) forward injection current. The observed changes in spectra are indicators of extreme sensitivity of dominant defects to relaxation of the disordered medium, and recombination enhanced reactions. Surprisingly the defect spectra is usually dominated by a single peak with unbroadened lineshape characteristic of discrete energy level in the bandgap, though electrical signatures keep varying for different processing conditions. In the light of these measurements, we discuss the nature of stability and metastability of the defects believed to be due to intrinsic defect clusters.

INTRODUCTION

Irradiation of MeV heavy ions is being considered as a processing tool in a variety of silicon technologies both in order to reduce number of processing steps and use it as a method of defect engineering [1]. In view of emerging applications, there is at present an intensive effort to study defects and defect processes in high dose MeV heavy ion implanted silicon [2]. Recently we have reported the role of dominant electrically active defects in controlling compensation in regions of implant induced damage in silicon and discussed their possible origin in formation of intrinsic clusters [3,4]. A crucial issue in processing technology is the stability of the defect clusters and changes in defect spectra under various processing conditions. A thorough understanding of evolution of defects on thermal annealing is a significant goal at present in attempts to correlate origin, size and distribution of clusters and their role in controlling various phenomena such as transient enhanced diffusion, defect-dopant interaction etc. In this work we show that the electrical defect spectra is extremely sensitive to annealing and processing conditions and discuss possible origin of such effects.

EXPERIMENTAL DETAILS

Damage is created in silicon using heavy ion beams of Ar⁺ (1.45MeV, dose 10¹³-10¹⁴ cm⁻²) at room temperature in a 2MeV Van de Graaf accelerator. Schottky barrier devices are made for capacitance based transient studies by evaporating gold dots of 1mm. The doses are high enough to create heavy damage without amorphization. The as implanted samples did not receive any other-high temperature annealing except for heating at 70° C for 30 minutes for curing the contact epoxy. Some finished devices were annealed at 160°C in an oven. Furnace annealings were carried out at 400 and 600 °C in vacuum for 30 minutes.

Characterization of electrically active defects in presence of severe disorder poses several problems invalidating routine analyses using techniques such as DLTS [4]. Hence constant-

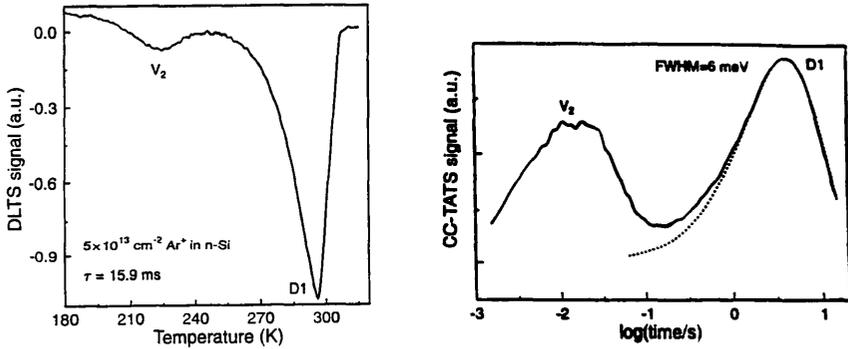


Fig. 1. (a) A typical DLTS spectrum of MeV Ar⁺ ion irradiated n-type silicon and (b) a typical CC-TATS spectrum showing a fit to a Gaussian energy distribution for D1.

capacitance voltage transients are used in conjunction with DLTS for survey purposes. In Time Analyzed Transient Spectroscopy (TATS) [5], the first order spectrum is given by

$$S(t) = C(t,T) - C(t+\gamma,T)$$

where $C(t,T)$ represents the isothermal transient at temperature T and γ is an experimentally chosen constant defining the width of the moving rate window. For exponential transient of time constant τ , $S(t)$ has a maximum when plotted against $\ln(t)$ and it occurs at a time t_m given by the relation,

$$\tau = \left[\frac{\gamma}{\ln(1 + \gamma)} \right] t_m$$

The peak value of the TATS signal is a measure of the strength of the exponential. One of the principal advantages of time domain spectroscopy such as TATS is that the lineshape of a peak is independent of the trap parameters or the range of time and temperature. This is in contrast to DLTS or any other temperature scanning spectroscopy.

The electrical transient studies reported here are carried out in a typical system, described elsewhere in more detail, including a fast Boonton capacitance meter (72B) and digitizer (Keithley 194). The system is automated and is capable of acquiring 20,000 sampling points for transients over four orders of magnitude in time typically from millisecond to hours. All spectroscopic operations as described above are implemented using software after complete acquisition of the transients.

For all the samples, the range of the ions were $1.2 \mu\text{m}$ from the surface. However the defects were observed in most cases about $1 \mu\text{m}$ deeper than that. The concentration of the observed defects at this distance was comparable to the shallow concentration. We also know from our earlier studies [4] that we are being able to populate only a fraction of the traps at the sharp edge of a defect dominated region within the depletion layer.

RESULTS AND DISCUSSION

Figure 1(a) shows a typical DLTS spectrum of n-type as-implanted silicon where D1 is the dominant defect controlling compensation as reported earlier and the peak labeled V_2 is due to the second ionization of the well known divacancy center at energy $E_c-0.42\text{eV}$. Due to various distortions inherent in DLTS spectra, defect parameters in these cases is best obtained by the use of CC-TATS analysis. A typical constant capacitance TATS spectrum corresponding to DLTS spectrum is shown in Figure 1(b). The activation energy of D1 from CC-TATS analysis is between $0.50\text{-}0.54\text{eV}$ with a capture cross-section of about $1 \times 10^{-15} \text{cm}^2$ in as implanted

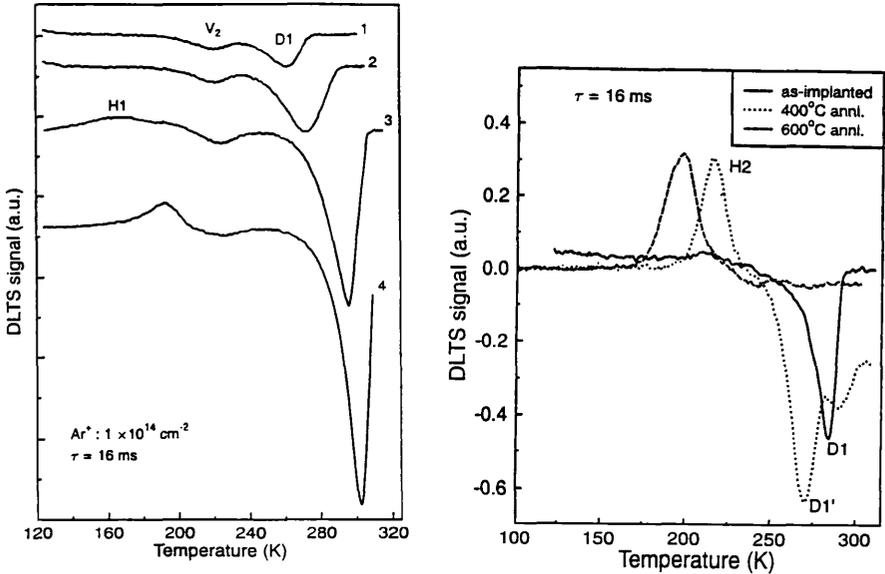


Fig.2. (a) DLTS spectra for (1) as-implanted, (2) after extensive multiple measurement cycles, (3) 160°C, 30 min anneal (4) 160°C 3 hours anneal. (b) comparison for vacuum annealings at higher temperature.

samples. It is important to point out here that the activation energy and other defect parameter determination has to be carefully done in presence of distortions in lineshape as shown previously [3]. The lineshape of the D1 peak corresponds to a defect with energy distribution corresponding to a Gaussian with FWHM of 6meV only. Hence the defect can be treated to be practically to a single level. The FWHM of Gaussian distribution in energy seems to increase with ion dose and provides with a convenient measure of disorder in the vicinity of the defect. We follow changes in defect spectrum under various annealing conditions specifically the defect corresponding to peak D1.

Figure 2(a) shows changes in DLTS spectra that accrue on room temperature usage and low temperature oven annealing of the samples. Curve 1 and 2 in the figure show the spectra taken under similar conditions on the same sample in an interval of two weeks within which it underwent several measurement cycles for electrical characterization. Though divacancy peak seem to be exactly matching for the two spectra, the damage related D1 peak is shifted towards higher temperature for the same rate window. Prior to these measurements, the samples were kept at room temperature for few months before devices were made on the irradiated wafers. Hence, room temperature annealing alone is not responsible for this behavior and it seems to get

induced with many cycles of measurement. Further possible explanation will be given later in this section. Effect of relatively low temperature oven annealing at 160 °C for 30 minutes is shown as curve 3 in Fig.2(a). In this case, the peak height of divacancy related peak is reduced and the D1 peak is shifted to further higher temperatures. This is attributed to relaxation of the damaged layer where defects D1 find a more stable configuration upon such low temperature annealing. The broad feature H1 seems to be related to a minority carrier trap due to injection of minority carriers from the compensated regions of the sample close to the surface.

Effect of further annealing at 160 °C for the irradiated sample is shown in curve 4 of the same figure. It shows increased peak D1 height with small shift in peak position. Note that this peak is substantially narrow as compared to the as-implanted case. We have discussed the cause of such narrowness in DLTS and TATS peaks elsewhere [3], attributing it to the particular sample configuration in which a large amount of defects cross the Fermi level within the depletion region. Minority carrier related peak height is increased in longer duration oven annealed samples. Thus low temperature annealing of the damaged layer shows more electrically active defects, and the emission energy of the dominant defect D1 goes deeper into the gap with annealing.

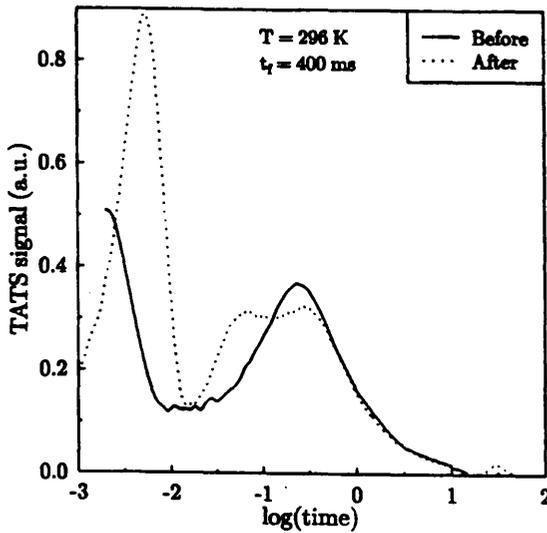


Fig.3. CC-TATS spectra for samples before and after forward biasing n-type sample containing damage layer.

Fig. 2(b) shows similar studies for higher temperature furnace annealing in vacuum for n-type samples. In contrast to as-implanted sample which showed divacancy related peak and D1 peak (solid line), 400 °C annealed sample shows a different DLTS spectrum consisting of two majority carrier related peaks and one minority carrier peak. The absence of V_2 peak is expected since they anneal out at ~350 °C. The peak position of the major defect is towards lower temperature side. Though DLTS analysis cannot be relied upon for proper estimation of trap parameters, nevertheless an approximate estimation refers to midgap level. Hence the major defects created in as-implanted samples are not annealed out by 400°C annealing, rather they form more stable defect complexes on annealing. By 600°C most of these defects are annealed out as shown in the Fig. 2(b). However C-V studies show that all defects are not annealed out by that temperature, only those detectable by DLTS are not seen in the range of filling. Though the

definite origin of the minority carrier related peaks in these spectra is not clear at the moment, it may be due to mild inversion in the damaged layer or injection from highly compensated region near the interface. Similar conclusions have been obtained from TSCAP analysis instead as well.

Interestingly injection of large forward current of few milliamps into the n-type Schottky diode at room temperature also changes the spectrum drastically. Figure 3 shows the comparison of CC-TATS spectra before and after such a forward biasing pulse for an unannealed sample of n-type Schottky sample. Note that divacancy peak remains at the same position but the dominant peak is shifted and gives rise to another majority carrier peak previously absent. Hence it is clear that this is the result of recombination enhanced reactions during which the defect configuration underwent relaxation. Also note that the concentration of the dominant trap gets increased.

Qualitatively similar results were obtained for p-type as well with some differences. The trends in results are best summarized in Fig4 where a series of DLTS spectra are shown for various annealing conditions. The defect parameters have been separately evaluated using CC-TATS analysis and gives an energy value of $E_v+0.52$ with a capture cross-section of $\sim 10^{-13}$ cm^2 . In all the spectra the activation energy remains quite midgap with signatures changing principally due to large changes in capture cross-section. A detailed quantitative correlation of these changes is currently underway and will be reported elsewhere. Suffice it to say that the spectrum is again extremely sensitive to annealing conditions. There is one principal difference between n-type and p-type damaged layers. For p-type samples 600°C annealing is not adequate to anneal out the major defect signatures. In fact the defect occurs in very large concentration and has an activation energy of 0.51 eV with a capture cross-section of 10^{-12} cm^2 . In p-type formation of newer complexes seem to be more pronounced than in n-type. We believe that these have the same origin as other interstitial related clusters reported in the literature [2]. Hence we have shown that electrical signatures of defects are very sensitive to processing conditions for MeV implanted regions in both n and p-type samples. The key questions that these empirical observations raise are : i) why is the defect spectrum so sensitive to low energetic provocations ? ii) In stead of changes in concentration as in conventional annealing why do they show changes in electrical signatures themselves ?

It is possible to say that evolution of configurational changes of the defect is responsible for such behavior. But it is not clear whether it is due to changes in the vicinity of the defect due to damage induced disorder or due to defect configuration itself.

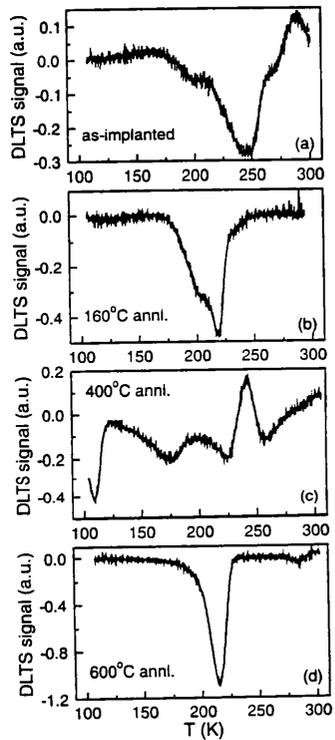


Fig.4. Comparison of DLTS spectra for (a) as-implanted, (b) 160°C annealed (c) 400°C annealed and (d) 600°C annealed Ar^+ implanted p-Si. The rate window for the DLTS scans shown is 16 ms.

It is tempting to ascribe it to formation of clusters and evolution towards 311 defects of interstitial nature as has been done in the literature[3]. Whether it is due to disorder in the environment or simply due to distribution of size of clusters, in either case we would expect a distribution of energy leading to increased linewidth of DLTS or CC-TATS spectra. We speculate that the relation of the activation energy of the electrically active trap probably gives rise to some non-intuitive distribution in energy such as a sharp exponential distribution or even a log-normal distribution. In that case we would be observing states with very narrow energy width at any particular time and annealing conditions seem to change these cluster size distributions only shifting the observed energy spectrum for various conditions. However we are far from convincing answers such as these and crucial designer experiments is likely to lead the course of investigations.

CONCLUSIONS

We have studied how electrical signature spectrum of defects created by MeV heavy ion implantation in silicon change with various annealing conditions. The defect spectrum is shown to be sensitive to processing conditions such as (i) many measurement cycles (ii) forward bias current, (iii) low temperature oven annealing and (iv) conventional furnace annealing. With low temperature annealings the dominant damage induced midgap defect in n-type seem to relax to configurations corresponding to deeper states in the gap. They however anneal out beyond 600°C. For p-type samples the changes are less monotonic in nature and seems to evolve through many complexes finally stabilizing at a midgap level of 0.51eV with very large hole capture cross-section of 10^{-12} cm² upon annealing at 600°C. The defects are ascribed to clusters though the understanding the reasons for such sensitivity to changes in processing conditions requires more detailed work.

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