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COMPARISON OF EFFECTS OF PULSED RUBY LASER AND PULSED ELECTRON BEAM ANNEALING OF $^{75}As^+$ IMPLANTED SILICON

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ABSTRACT

Ion-backscattering, ion-channeling, and transmission electron microscopy (TEM) have been used to study a series of ion implanted silicon samples that have been annealed with either a pulsed laser or a pulsed electron beam. Single crystal [(001) orientation] silicon samples were implanted with either 35 or 100 keV $^{75}As^+$ to a dose of $\sim 1 \times 10^{16}$ As/cm^2 and subsequently annealed with either a Q-switched pulsed Ruby laser or the Spire Corporation SPI-PULSE 5000 electron beam generator. A series of energy densities was used in both cases to optimize results. It was determined from Rutherford backscattering that the as-implanted profiles have been redistributed in essentially the same manner for both types of anneals, and this indicates that melting and rapid recrystallization has occurred. For the 35 keV $^{75}As^+$ implanted samples the two techniques produced equivalent anneals with no remaining damage as indicated by channeling and TEM. However, for the 100 keV implants the anneal was not uniform across the sample in the electron beam case and the channeling minimum yields for the major axes ([110], [111], and [100]) were higher than the laser annealed results. In both cases, however, the As substitutionality (97-99%) and minimum yields are better than results obtained from conventional thermal annealing.

INTRODUCTION

Ion implantation, because of its precision and reproducibility has been used for several years as a method of mass producing p-n junctions in semiconductor devices. However, a major problem with ion implantation is the removal of damage created in the crystal by ions coming to rest. In the case of silicon, ion implantation will leave the near-surface region heavily damaged or even amorphous. In addition, the implanted dopants will not occupy substitutional lattice sites and thus will not be electrically active. Therefore, the key to wider use has been the ability to anneal the radiation damage in the crystal and to incorporate the implanted species onto electrically active substitutional lattice sites. Recently intense interest has been generated in the possibility of using a pulsed laser[1,2] or a

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pulsed electron beam[3,4] for annealing ion implanted silicon. Both techniques use high energy density, short-time duration ($\sim$ 50 x 10^{-9} sec) pulses to heat only the near-surface region of the implanted crystal. These pulses cause the implanted region to melt, followed by liquid phase epitaxial regrowth on the underlying crystal. This differs significantly from conventional thermal annealing where the entire sample is heated to several hundred degrees for 30 minutes or longer. This usually results in incomplete annealing with dislocations, dislocation loops or stacking faults remaining and part of the implanted dopants not being activated.

Ion-channeling backscattering analysis and transmission electron microscopy (TEM) have been used to compare $^{75}As^+$ implanted samples that have been annealed with a Q-switched ruby laser or with a pulsed electron beam. Our results show both pulsed annealing techniques produce superior anneals to those previously reported for thermal annealing. We have found that the pulsed electron beam did a better job of annealing a 35 keV $^{75}As^+$ implant than a 100 keV implant where the anneal was not uniform across the crystal. These problems were not observed for the laser annealed samples.

SAMPLE PREPARATION

Boron doped, single crystal silicon samples, that had been cut and polished parallel to the (001) face were implanted with either 35 or 100 keV ^{75}As to a dose of $\sim$ 1 x $10^{16}/cm^2$. Implants were carried out at room temperature, under high vacuum conditions, and with a beam current density of $\sim$ 2 microamps per square centimeter. Samples were tilted 5° with respect to the incident beam to minimize channeling of the $^{75}As^+$ ions.

The pulsed laser annealing was performed in air using the Q-switched output of a ruby laser (0.694 μm wavelength) at energy densities of 1.5 to 1.7 J/cm^2. The laser pulse duration was typically 50 nanoseconds. The coupling of electromagnetic energy into silicon has been discussed in detail.[5]

The Spire Corporation SPI-PULSE 5000 electron beam generator[3,4] was used for the pulsed electron beam annealing. The 35 keV implant was annealed with a 0.9 J/cm^2 pulse. The best results for the 100 keV implants were for e^--beam fluences of 1.1 to 1.2 J/cm^2 pulses. For lower energy density pulses not all of the implantation damage was removed and e^--beam fluences greater than 1.2 J/cm^2 produced cracks in the sample surface.

RESULTS AND CONCLUSIONS

The arsenic implanted crystals were analyzed before and after pulsed annealing using 2.5 MeV He^+ backscattering-channeling techniques and transmission electron microscopy to study the quality of the anneal and the dopant profile changes. Channeling spectra taken with the beam aligned with a major axial direction ([100], [110], and [111]) were used to study the damage distribution before and after annealing. These channeling spectra and detailed angular scans across the [110] axis were used to determine the fraction of implanted arsenic atoms that reside on substitutional lattice sites after pulsed annealing. Procedures for channeling studies have been well documented.[6,7] In order to minimize the effects of the analyzing beam[8,9] each channeling spectrum was recorded with the beam incident on fresh spots that had not been exposed to the beam. These spectra were normalized to random spectra that were obtained while continuously rotating the crystal about an axis through the sample normal. This tends to average out channeling effects and results in a spectrum that is typical of an amorphous material. The random spectra were also used in determining the dopant profiles.

Backscattering analysis has been used to study the ^{75}As profiles in the as-implanted and pulsed-annealed conditions. Figure 1 presents the profile data for the 100 keV implant electron beam annealed sample and shows a signficant redistribution of the dopant both toward and away from the surface. This results in an As concentration that is almost uniform to a depth of ∿ 1200 Å and then falls off exponentially.

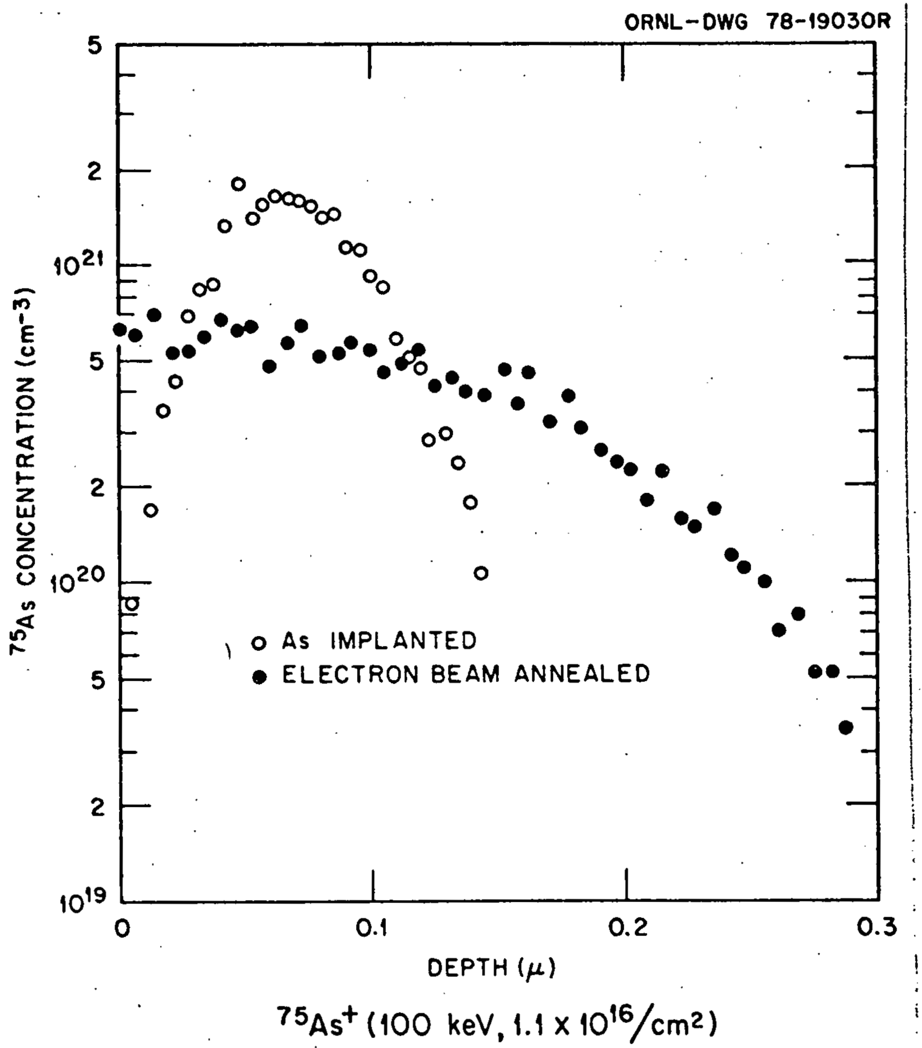


Fig. 1. ^{75}As profile in the as-implanted and pulsed electron beam annealed condition.

This profile is very similar to the laser annealing profile, for which it has been determined that the near-surface region has melted to a depth of several thousand angstroms.[10,11] This strongly suggests that surface melting and dopant redistribution by diffusion in the melt has occurred in this case as well.

High resolution aligned axial channeling spectra, taken before and after electron beam annealing are presented in Fig. 2. Data from a virgin sample have been included for comparison. This figure is similar to one presented in a companion paper for a laser annealed sample.[12] Since the silicon yield in the channeling direction is equivalent to the reference random across the implanted region, it can be concluded that the pre-anneal implantation damage is sufficient to turn the crystal amorphous to a depth of ∿ 1600 Å. From this figure it is seen that all of the implanted ^{75}As is located in this amorphous region. After pulsed electron beam annealing the yield of particles scattered from the implanted region is slightly higher than the yield from the virgin sample indicating that the amorphous region has been converted to good quality single crystal. The small differences between the annealed and virgin channeling spectra are probably due to near-surface effects. The substantial reduction in scattering from As after annealing means that most of the implanted dopant has been incorporated into substitutional lattice sites.

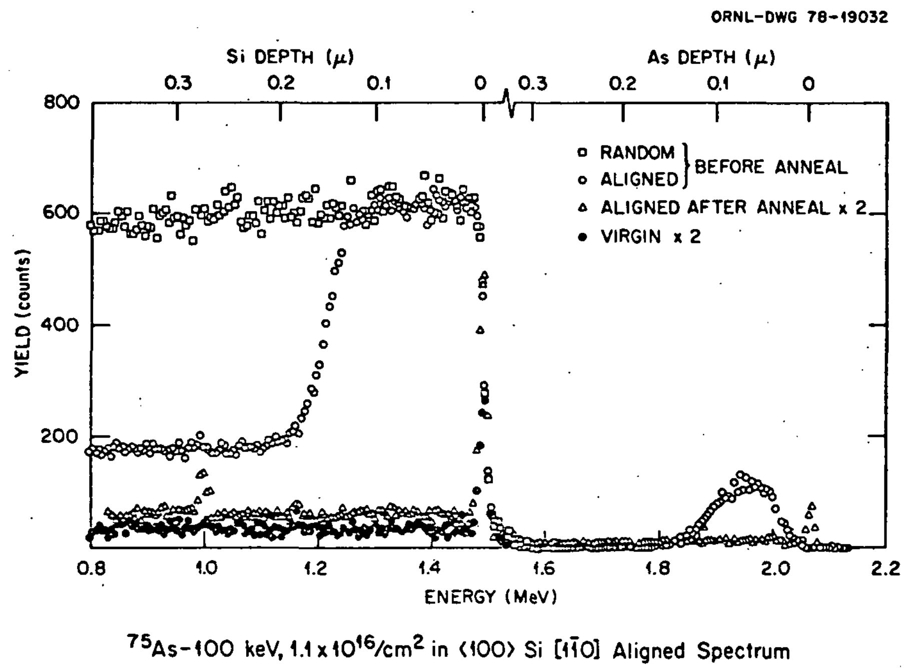
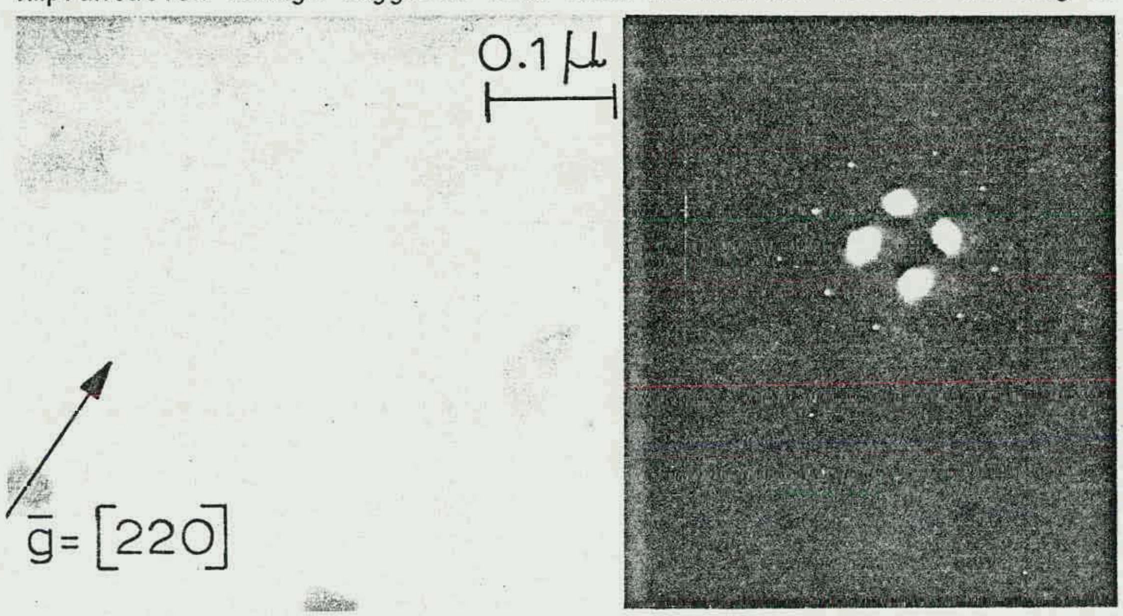


Fig 2. Composite [110] channeling-backscattering spectra for ^{75}As implanted silicon, before and after pulsed electron beam annealing.

Transmission electron microscopy (TEM) techniques were used to study the residual damage in ion implanted, electron beam annealed specimens. Figure 3a shows a bright-field electron micrograph of a specimen which was chemically thinned from the back side while masking the annealed layer. No damage in any form (dislocations, loops, precipitates or stackup faults) was observed in the implanted specimens after the electron beam annealing. This result is similar to that obtained from implanted, laser annealed specimens.[1,2] Figure 3b is a selected area diffraction pattern showing that the implanted layer has the same orientation (001) as the underlying substrate. Furthermore, the regularity of the spot pattern indicates high crystal perfection of the lattice in the implanted layer.

The lattice location of the implanted As after pulsed annealing has been studied using aligned channeling spectra and detailed angular scans. These results are discussed in detail in a companion paper.[12] Table I presents χ_{min} values and substitutional fractions for the 100 keV implant, electron beam annealed sample. These results show that the As is greater than 97% substitutional along each axis. Except for the χ_{min} values associated with the [111] axis these results are comparable to those obtained after laser annealing.[12] The [111] $_{min}$ (Si) was high because there was a large spot to spot variation in the quality of anneal across the surface of the 100 keV implant, electron beam annealed sample. The χ_{min} associated with the [110] axis varied from 2.64 to greater than 6% across the best electron beam annealed sample. However, the anneal was very uniform across the 35 keV implant, electron beam annealed sample and minimum yields for this sample were as good as those obtained from laser annealing.[12]

In conclusion, we have seen that pulsed electron beam and pulsed laser annealing give essentially the same results under optimum conditions. The redistribution of the implanted dopant and removal of implantation damage suggests that both mechanisms involve melting of



(a) (b)

Fig. 3a. Transmission electron micrograph (bright field) showing no damage in the arsenic implanted, electron beam annealed specimen.

Fig. 3b. Selection area diffraction pattern (001) of the implanted layer.

several thousand angstroms near the surface followed by liquid phase epitaxial regrowth. This incorporates greater than 97% of the implanted As onto electrically active substitutional lattice sites, which is considerably higher than has been reported for conventional thermal annealing.[7]

Two major differences were observed in the two types of anneals. After electron beam annealing traces of tungsten ($\sim 5 \times 10^{12}/cm^2$) were observed on the samples by Rutherford backscattering. This probably came from the tungsten anode of the electron beam generator. Also, after the sample has been annealed with one pulse from the electron beam, a second pulse will cause cracks,[3] whereas up to 13 consecutive laser pulses have been used with no residual damage. These cracks were also observed for e^--beam annealing fluences greater than ~ 1.2 J/cm^2 and are what cause the χ_{min} values from the 100 keV implant electron beam annealed sample to be nonuniform across the surface. This indicates the electron beam is not completely uniform. The cracks may be caused by charge build up since they were not observed for the 35 keV implant where a lower electron beam fluence was used. The origins of the differences in damage resulting from the two pulsed annealing techniques are not known. It may be related to the differences between the absorption mechanisms in amorphous and single crystal silicon for photons and electrons.

Table I: ^{75}As (100 keV, $1.1 \times 10^{16}/cm^2$) in Si, Pulsed Electron-Beam Annealed

Axis	χ_{min}(Si) (%)	χ_{min}(As) (%)	Fraction Substitutional (%)
[110]	2.64 ± .05	3.27 ± .29	99.35 ± .29
[$\bar{1}$10]	2.63 ± .04	5.52 ± .29	97.03 ± .29
[100]	3.58 ± .06	4.73 ± .42	98.81 ± .42
[111]	5.63 ± .06	6.84 ± .41	98.72 ± .41

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