Athermal annealing of low-energy boron implants in silicon

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Silicon samples that have been ion implanted with boron at energies below 3 keV have been athermally annealed. The annealing process has been characterized using secondary ion mass spectrometry and infrared absorption spectroscopy. The athermally annealed samples show activation comparable to that for thermally annealed samples, but with much less boron diffusion. The activation in the athermally annealed samples is shown to be much higher than would be achieved by recrystallization of the amorphous layer. © *2001 American Institute of Physics.*
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As device dimensions in integrated circuits shrink, the need for shallow boron implants at low energies becomes more imperative. The production of shallow boron implants, however, is hampered by transient enhanced diffusion (TED) of boron during implantation and annealing.[1–3] In order to assess its effectiveness at reducing TED, we have investigated the athermal annealing process[4–7] on shallow boron implants.

The experiments were performed on 100 mm Czochralski silicon wafers that were implanted in two different ways. The first samples were implanted with $^{11}B^+$ at an energy of 1 keV and a dose of $3.3\times10^{14}\,cm^{-2}$. At this energy, the implant does not amorphize the silicon. The second set of samples were preamorphized with a germanium implant of 5 keV and a dose of $1\times10^{15}\,cm^{-2}$, followed by an $^{11}B^+$ implant at 3 keV and a dose of $1\times10^{15}\,cm^{-2}$. These two doses and implant energies were chosen because they are representative of implants being considered for shallow junction fabrication processes. Control samples of both types were thermally annealed at 900 °C for 1 h in a N_2 atmosphere. In addition, a preamorphized sample was annealed at 550 °C for 1 h in order to recrystallize the amorphous layer by solid phase epitaxy,[8] to serve as a control on whether the athermal process was simply recrystallizing the amorphous layer. The athermally annealed samples were subjected to a single laser pulse of approximately 7 J, 35 ns in duration, focused to ~2.5 mm. The laser wavelength was 1.06 μm. Annealing was observed in a circular area approximately 1 cm in diameter centered on the laser focal spot.[7] Efforts to increase the annealed area are currently being performed. Secondary ion mass spectrometry (SIMS) and infrared absorption measurements were then performed on all of the samples.

SIMS results for as-implanted, thermally annealed, and athermally annealed samples are shown in Fig. 1. For the athermally annealed samples, the measurements were made within the annealed region, but far enough away from the laser crater to avoid any effects due to surface roughness or heat from the laser. As expected, significant diffusion is observed in the thermally annealed control samples. One parameter used to assess the degree of diffusion is the depth at which the concentration falls below a certain value. For these experiments, we are using a concentration value of $1\times10^{18}\,cm^{-3}$ to determine the degree of diffusion. Using this value, the diffusion in the thermally annealed samples increases by a factor of approximately 3 in the preamorphized sample, and approximately 4 in the nonpreamorphized sample. Doses obtained by integrating the SIMS profile for the boron implant alone were $1.6\times10^{14}\,cm^{-2}$ for the as-implanted sample, $2.6\times10^{14}\,cm^{-2}$ for the athermally annealed sample, and $5.0\times10^{13}\,cm^{-2}$ for the thermally annealed sample. We speculate that the higher calculated dose in the athermally annealed sample is due to increasing surface roughness closer to the laser focal spot.[9] Increased surface roughness interferes with the trajectories of the secondary ions, delaying their arrival in the mass spectrometer. This causes the measured profile to be ''smeared,'' somewhat, resulting in a higher calculated dose. Actual surface roughness was not measured because it was not considered to be an important parameter. Subsequent experiments will include surface roughness measurements. The lower integrated dose in the thermally annealed sample is due to out diffusion of boron at the surface during annealing. Corresponding doses for the preamorphized sample are $9.3\times10^{14}\,cm^{-2}$ for the as-implanted, $9.7\times10^{14}\,cm^{-2}$ for the athermally annealed, and $4.6\times10^{14}\,cm^{-2}$ for the thermally annealed sample. By contrast, the amount of diffusion in the athermally annealed samples is significantly lower than in the thermally annealed samples. In fact, the profile of the athermally annealed samples is very similar to the as-implanted profile. In the nonpreamorphized sample, the depth at which the concentra-

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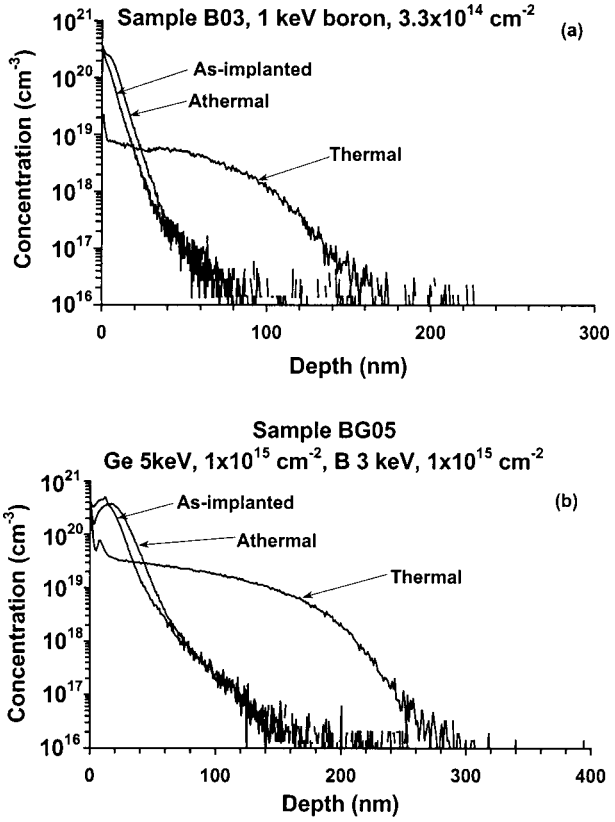

FIG. 1. SIMS profiles for both types of sample under different processing conditions. (a) Subamorphizing boron implant only. (b) Boron implant after preamorphization with germanium. The dopant profile is spread substantially by thermal annealing in both cases, but is changed very little by the athermal process.

tion reached $1\times10^{18}\,\mathrm{cm}^{-3}$ increased from 28.2 nm in the as-implanted sample to 32 nm in the athermally annealed sample. In the preamorphized sample, the depth increased from 71.4 nm in the as-implanted sample to 74.9 nm in the athermally annealed sample. For comparison, rapid thermal annealing leads to an approximately 30% increase in depth, depending on annealing parameters.[10–12]

In order to assess the active concentration, infrared absorption measurements were performed. At the concentrations present in these samples, individual donor excitations cannot be observed, because the impurities have formed a band. However, by measuring free carrier absorption, one can assess the active carrier concentration. In fact, the minimum in the free carrier absorption is determined by the free carrier concentration and the hole effective mass.[13] Infrared spectra for the boron implants are shown in Fig. 2. The as-implanted sample exhibits the characteristic infrared spectrum for intrinsic silicon. The peaks at low frequency are due to interstitial oxygen and lattice vibrations. There is no evidence of free carrier absorption in the spectrum of the thermally annealed sample. Free carriers in a sample cause an increase in the absorption with decreasing frequency, and the frequency at which the increase begins is related to the plasma frequency for the carriers. We speculate that significant amounts of the implanted boron diffused out of the surface during thermal annealing, leading to a reduced active concentration of boron in the sample. This conclusion is consistent with the SIMS data as well. The athermally annealed sample shows an increase in the absorbance with decreasing

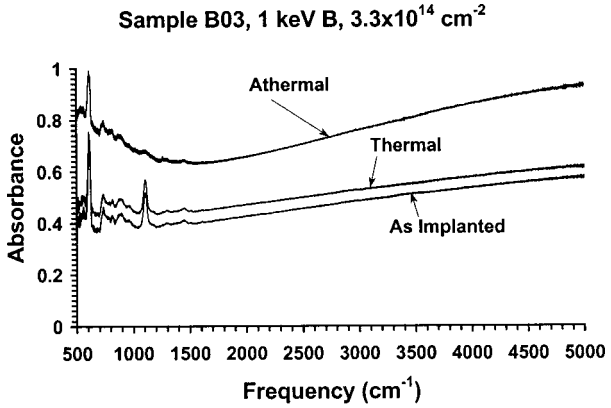

FIG. 2. Infrared spectra of subamorphizing boron implant under different processing conditions. The lack of free carrier absorption in the thermally annealed sample is due to out diffusion of boron from the surface.

frequency. This increase is due to the presence of free carriers in the material. The frequency at which the minimum in the absorbance occurs is related to the free carrier concentration in the sample. For frequency in cm^{-1}, the relation is [13]

$$\upsilon_{\min}=\sqrt{\frac{\pi c^2(\epsilon_\infty-1)m^*}{e^2N}},$$

where c is the speed of light, e is the electron charge, ϵ_∞ is the dielectric constant of the undoped crystal, m^* is the carrier effective mass, and N is the free carrier concentration. In this concentration regime, the effective mass is relatively constant, and is equal to approximately $0.3m_0$.[14] The absorbance minima were determined by fitting a function to the spectrum using nonlinear least squares methods, and taking the derivative of the fitted function to find the minimum. For the athermally annealed sample, the absorbance minimum occurs at a frequency of $1511.6\pm0.5\,\mathrm{cm}^{-1}$. This corresponds to a free carrier concentration of $8.19\pm0.01\times10^{19}\,\mathrm{cm}^{-3}$. This number correlates well with the SIMS results, indicating that the active concentration in the athermally annealed samples is close to the implanted concentration.

The infrared spectra for the preamorphized samples are shown in Fig. 3. In addition to the as-implanted, thermally annealed, and athermally annealed samples, a fourth sample is included that was heated at 550 °C for 1 h in order to recrystallize the amorphous layer. The as-implanted and re-

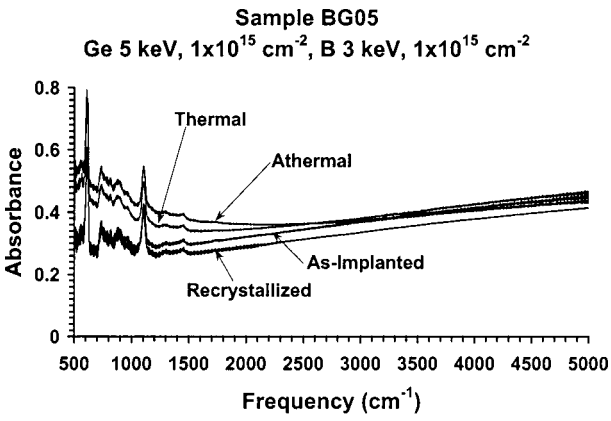

FIG. 3. Infrared spectra of boron implant with germanium preamorphization under different processing conditions. Free carrier absorption is observed in both the thermally annealed and athermally annealed samples.

crystallized samples are virtually identical, indicating that the active concentration in the recrystallized sample is not high enough to cause changes in the absorbance, at least in this frequency range. The implication of this result is that the athermal process is actually annealing and activating the implant, and is not just recrystallizing the amorphous layer. Both the thermally annealed and athermally annealed samples exhibit free carrier absorption, indicating a high concentration of free carriers in both samples. The absorbance minimum occurs at a frequency of $2215.6 \pm 0.5\,\mathrm{cm}^{-1}$ in the thermally annealed sample, and $2154.9 \pm 0.5\,\mathrm{cm}^{-1}$ in the athermally annealed sample. These minima correspond to free carrier concentrations of $1.16 \pm 0.01 \times 10^{20}\,\mathrm{cm}^{-3}$ for the athermally annealed sample, and $1.66 \pm 0.01 \times 10^{20}\,\mathrm{cm}^{-3}$ for the athermally annealed sample. Again, these results are consistent with the SIMS results, indicating that a large fraction of the implanted dose has been activated by the athermal processing.

In conclusion, we have demonstrated athermal annealing of low-energy boron implants in silicon. The annealing process produces almost no diffusion, and certainly much less than thermal annealing. The active concentrations achieved in the athermal process are comparable to those achieved in the thermal process, and much higher than those obtained by recrystallizing the amorphous layer. We therefore conclude that the athermal process actually anneals the silicon and does not just recrystallize the amorphous layer. The fact that the process is effective on subamorphizing implants, such as the direct boron implants used in this letter also supports this conclusion.

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