reflectivity that needs to be considered. Using the measured coefficient of thermal reflectance[13] $(1/R_0)(dR/dT) = +1.5\times10^{-4}/^\circ\mathrm{C}$, we can readily see that the thermal wave-induced modulation of the optical reflectivity is of the same order as, and of opposite sign to, the corresponding plasma wave effect. According to these arguments then, one can expect a net modulation of the optical reflectivity of Si of $\approx 10^{-5}$. Our experimental results[14] on Si are consistent with this observation. That is, the reflectance signals we measure on Si samples are usually smaller (sometimes by an order of magnitude) than predicted on the basis of there being only a thermal wave present in the material. We should point out that by changing the wavelength of the pump beam, one can in principle control the relative amounts of thermal wave and plasma wave effects on the modulated reflectance signal. For wavelengths closer to the band gap and at high enough modulation frequencies, the plasma wave can be made to completely dominate the signal. By going to shorter wavelengths one increases the thermal wave effect, and as the modulation frequency is lowered, recombination effects on the thermal wave can become significant.

In Fig. 2 we show results of calculations for a layer on a substrate in which both the thermal wave and plasma wave are contributing to the modulated reflectance as discussed above. For the substrate we assume parameters appropriate to crystalline Si. That is, $\kappa = 1.42$ W/cm °C, $\rho = 2.33$ g/cm^3, $C = 0.703$ J/g °C, and $D = 20$ cm^2/s. For the layer we assume a damaged or amorphous Si (e.g., as produced by ion implantation), with $\kappa = 0.03$ W/cm °C and $D = 0.1$ cm^2/s. For the thinner layers and at the lower modulation frequencies, the thermal wave is dominating the signal. As the layer thickness increases, however, the plasma wave begins to dominate as is most easily seen in the phase which saturates at 225°. One can, from an analysis of the magnitude and phase dependence of the modulated reflectance signal, determine the thickness and material properties of the damaged layer.

In conclusion, we have described a depth profiling concept based upon the critically damped plasma wave corresponding to the free-carrier plasma produced in a semiconductor by an intensity modulated energy source. Analogous to the thermal wave as a probe of local variations in thermal features, this plasma wave is of practical significance in that it can be used to detect and measure changes in material properties that affect its propagation. In some cases, as in ion implanted semiconductors, we expect the plasma wave to be affected much more significantly than the thermal wave. In most cases involving semiconductors, we believe the plasma wave will provide a complementary capability to the thermal wave as a technique for materials characterization.

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High-quality Si-implanted GaAs activated by a two-step rapid thermal annealing technique

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The properties of Si-implanted GaAs activated by halogen lamp annealing have been studied. It is found that consistently better results can be obtained by a two-step annealing technique in which the high-temperature main anneal step is followed by a second anneal at a lower temperature. Mobilities and activations of 4000–4600 cm^2/Vs and 50–65%, respectively, are obtained for $(3.0\text{–}6.5)\times10^{12}$ cm^{-2}/100 keV $^{29}\mathrm{Si}^+$ implants. These values are among the best reported for lamp-annealed GaAs. Raman spectra confirm the high quality of the annealed crystals.

Rapid thermal annealing (RTA) is now being extensively used for the activation of implanted dopant species in GaAs.[1-3] Several advantages in using RTA have been envisaged. Low dopant and background impurity diffusion and redistribution, absence of encapsulation or As overpressure requirements, and a possible reduction of electrically active

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complex defects are some of the favorable attributes. Typical incoherent light sources used for RTA are high-power halogen lamps, arc lamps, and radiating resistance heaters.

The main objectives of RTA are to obtain high mobilities and activations reproducibly and to obtain annealed wafers of quality comparable to or better than that obtained by conventional long-term furnace annealing. The experimentation, with a variety of heat sources, is still in the early stages. Some key questions, related to the uniformity of the process over large-area wafers and the reproducibility of the process, still remain. With this objective in mind we have studied halogen lamp annealing of GaAs and have established annealing parameters which (depending on starting substrate materials) give active layer characteristics comparable to the best obtained by furnace annealing. In particular, we find that a two-step annealing procedure gives slightly better and more reproducible results than single-step RTA. The implanted and annealed wafers have been characterized by Hall measurements, low-temperature photoluminescence, and Raman spectroscopy.

Direct implantation with 100 keV $^{29}Si^+$ was done on (100) oriented, undoped, liquid encapsulated Czochralski (LEC) GaAs. Before implantation 5–10 μm of the polished surface was usually etched. Three doses were used for this study: 3.0, 4.7, and 6.5×10^{12} cm^{-2}. The implanted samples were annealed in a HEATPULSE 210T halogen lamp annealing station under flowing ultrapure N_2. The annealing temperatures are measured by a chromel-alumel thermocouple contacted to a monitor Si wafer and are controlled by closed-loop feedback control. We consistently obtained the best results, in terms of surface morphology and electrical and optical characteristics of the wafer, by using a GaAs proximity cap. The implanted side of the experimental wafer faces up and is covered by a polished LEC undoped GaAs wafer.

As mentioned earlier, both one- and two-step lamp annealing were investigated. In the latter process, a second anneal pulse at a lower temperature (800–850 °C) is applied for a longer time either before or after the main anneal pulse. The results obtained from one- and two-step annealing are illustrated in Fig. 1. The samples used were implanted with 6.5×10^{12} cm^{-2} Si^+. Each data point is an average over several samples. The data indicate that two-step annealing gives better mobility and activation than one-step annealing at 900 °C for 5 s. The lowering of mobility beyond 30 s of 850 °C anneal in the two-step process is probably due to As loss. This is evidenced by the morphology of the annealed layers. Similar observations have been made by other authors.[3] The mobility and activation values illustrated in Fig. 1 are among the highest reported for samples implanted with Si of equal or comparable dose and energy and activated by RTA or conventional furnace annealing.[4]

Variations of mobility and activation with implant dose in samples activated by the two-step annealing process are shown in Fig. 2. Once again, the consistently high values of these parameters are evident.

We have also investigated the uniformity of the two-step annealing process. In particular we have measured the uniformity in Hall mobility, activation, and low-temperature photoluminescence integrated intensity over 2-in. wafers. Results are shown in Fig. 3 for samples implanted with 6.5×10^{12} cm^{-2} Si^+ at 100 keV. The variation in mobility in the radial direction is within 5–10%. The activation profile usually follows the PL intensity profile. The overall superiority of the two-step anneal process is clear.

Raman scattering is usually very sensitive to residual

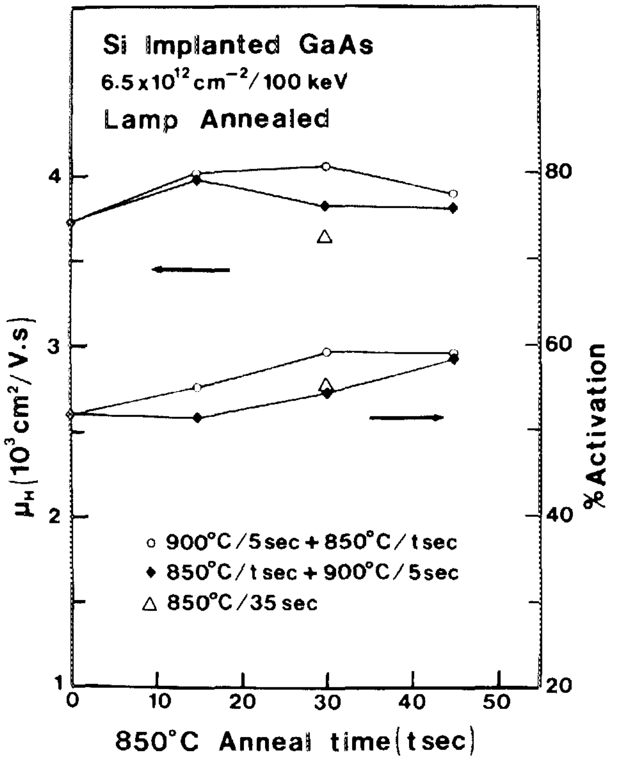

FIG. 1. Mobilities and activations in Si-implanted undoped LEC GaAs activated by one- and two-step halogen lamp annealing.

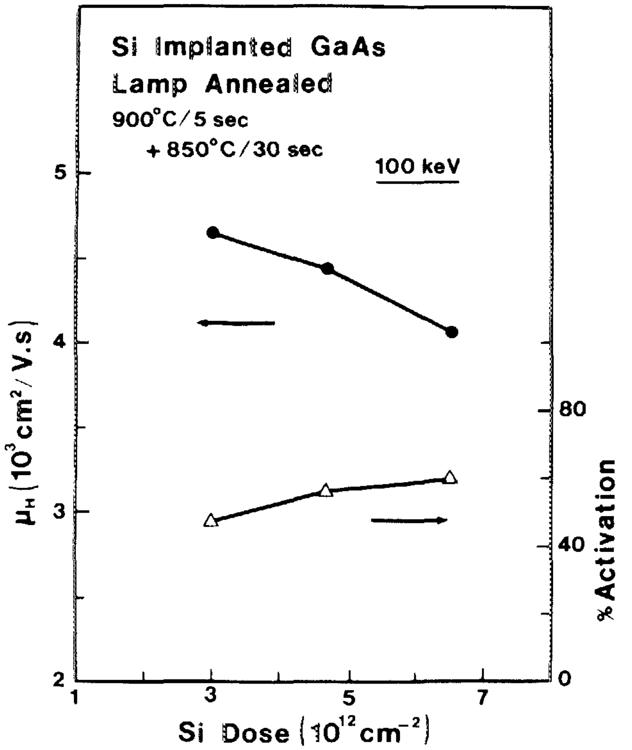

FIG. 2. Variation of mobility and activation with implant dose in Si-implanted GaAs activated by two-step halogen lamp annealing.

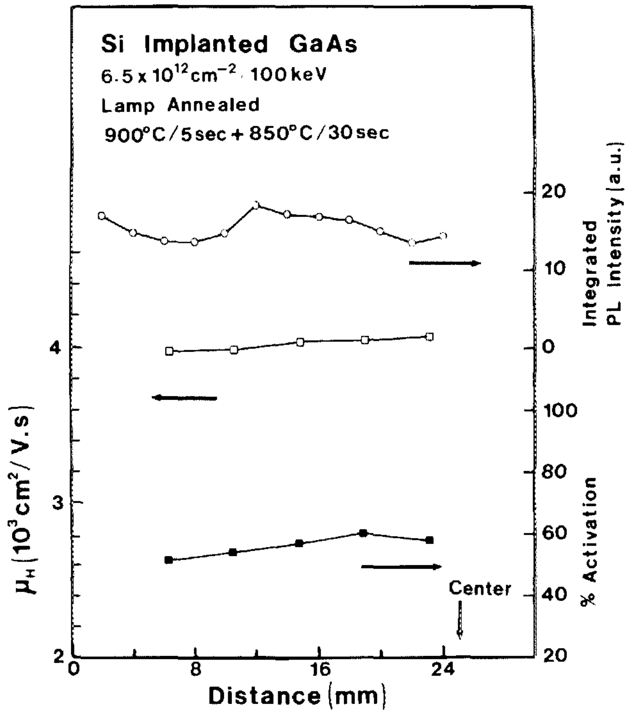

FIG. 3. Radial profiles of integrated photoluminescence intensity, Hall mobility, and activation in 2-in.-diam Si-implanted GaAs activated by two-step halogen lamp annealing.

implant damage, surface depletion effects, mobility, and carrier activation.[5] Preliminary Raman spectroscopy was done with the samples at 4, 77, and 300 K. The backscattered light from the sample was analyzed with a Spex double monochromator. The data for high-quality furnace-annealed GaAs and our RTA samples were almost identical in the region of dominant first-order scattering. The expected LO phonon mode from the surface depletion layer and the coupled LO phonon-plasmon modes are observed. The LO phonon linewidth is very narrow and is between two and three wave numbers. This indicates the high quality of the activated crystals.

We have performed complementary deep level measurements on Schottky barriers made on the implanted layers. Details of these measurements will be published elsewhere. In general we find that deep level traps, which can be attributed to substrate defects and implant damage, are almost absent in two-step annealed samples. Trap densities are significantly lower than those in one-step annealed samples. We therefore believe that the improvement in the quality of the two-step annealed samples is due to a reduction of defects in the active layer, interface region, and dislocation band just below the active layer. Transmission electron microscopy studies are being planned to ascertain this. Finally, the activation efficiencies reported here should be briefly discussed. Our data are obtained from Hall measurements. If corrections for surface depletion are applied,[6] the resulting activations are of the order of 85–95%.

To ascertain the cause of improvement in the crystalline quality by two-step annealing, supplemental annealing with the low-temperature step varying in the range 750–900 °C was done. Variations in the temperature of the second step between 800 and 850 °C did not produce any noticeable difference in mobility and activation consistently and yielded superior annealed layers. Above this temperature, As loss from the surface is observed. We conclude that very short or very long duration single-step anneals give non-optimal results due to insufficient damage annealing or the onset of nonstoichiometry, respectively. Two-step annealing probably provides a compromise between the two extremes.

In conclusion, we have demonstrated that a two-step halogen lamp annealing technique consistently gives high mobilities and activations. From Raman spectroscopy and other measurements it appears that the improvement results from a reduction of defects and strain in the active layer and the dislocation band underneath it.

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