perconductor at the transition temperature. We have also found, from the photoacoustic measurements, that the superconducting transition at the offset temperature is a second-order transition with no latent heat. Using the RG theory, the specific heat anomaly of the superconductors at the transition temperature has been qualitatively derived from the PA signal intensity measured. If the thermal conductivity data for the samples are available, it is expected that the specific heat anomaly can be analyzed more quantitatively.

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Recombination velocity at molecular-beam-epitaxial GaAs regrown interfaces

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We have estimated the recombination velocity and minority-carrier diffusion length at and near molecular-beam-epitaxial GaAs regrowth interfaces. The diffusion length in the regrown layers is ~ 1–$3\ \mu$m and is lowered to $0.3\ \mu$m at the interface. The interface recombination velocity is $\sim 10^5$ cm/s. These parameters are better for a sample which was ion milled and lamp annealed before regrowth, compared to a sample which was wet-chemical etched and annealed in the growth chamber under arsenic flux before regrowth.

Molecular-beam-epitaxial (MBE) regrowth of GaAs has received much attention in the recent past [1-3] because successful MBE regrowth may be necessary for the realization of advanced and novel devices.[4] Although some devices have already been fabricated using MBE regrowth[5,6] the electrical characteristics of the regrowth interface is not well understood to date. The regrowth interface has associated with it an anomalous depletion and accumulation of carriers which leads to a high resistive region around the interface.[1-3] It is believed that the anomalous carrier distribution is caused by a disordered region at the growth interface.[2,3,7-10] We have recently observed[3] that the nature of the depletion-accumulation observed at the interface is dependent on the type of processing that the GaAs surface is exposed to, before regrowth. The electrical characteristics of regrowth interfaces of ion-milled GaAs surfaces are found to be much better than chemically etched ones. In this communication, minority-carrier recombination velocities measured at the MBE GaAs regrowth interfaces are being reported for the first time.

Light-beam-induced current (LBIC)[11-18] and electron-beam-induced current (EBIC)[12] scans are established methods for characterizing minority-carrier diffusion lengths and recombination velocities both in the bulk and at discontinuities such as those encountered in grain boundaries of polycrystalline material. In this study we have used the LBIC technique to measure the recombination velocity and diffusion lengths of minority carriers at the GaAs homoepitaxial regrowth interface. Since the electrical behavior of the dis-

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continuity at the regrowth interface is somewhat similar to that of a grain boundary,[2,3,7-10] the models of Zook,[11,12] Watanabe *et al.*[13] and Ashley and Biard[14] could be successfully used to analyze the measured data. The experimental method used is similar to that of Mimilla-Arroyo and Bourgoin.[15] The models used have their merits and demerits discussed elsewhere so the results from all of them are presented for comparison.

MBE growth and regrowth were done in a Varian Gen II MBE System. The first step was to grow a 1.5-μm *n*-GaAs doped with silicon (1×10^{16} cm^{-3}) on a silicon doped n^+[100] GaAs substrate. The substrates were solvent degreased, etched in H_2SO_4:H_2O_2:H_2O (5:1:1) for 90 s at 60 °C and finally etched in HCl:H_2O (1:1) before mounting on the molybdenum holders. Before commencing growth the residual oxides were desorbed at 630 °C and an arsenic stabilized surface was established by *in situ* monitoring of the electron diffraction pattern. Growth and regrowth were carried out at 0.8 μm/h, at 610 °C. After the first growth the GaAs layer was removed from the chamber and a piece of it (sample A) was etched in NH_4OH:H_2O_2:H_2O (3:1:50) for 60 s and was reinstated in the chamber for regrowth. Before commencing regrowth, the wafer was annealed in an arsenic flux for 20 min and regrowth was carried out. Another piece of the first grown layer (sample B) was ion milled in a Millatron system and was annealed for 7 s at 900 °C in a Heat Pulse 210 halogen lamp annealing system before putting it back into the growth chamber. The thickness of the regrown layer was $\simeq 1.4$ μm. Gold Schottky barriers were fabricated on the regrown GaAs layers and a row of Schottky diodes were angle lapped at 5.7°, after which a contact was bonded to the Schottky diode. For the measurement of the interface recombination velocity, the lapped devices were suitably mounted and light from an Ar^+ laser was focused (~ 2 μm diam) on the bevelled surface. The induced photocurrent was detected and recorded using lock-in amplification. Response of the light scan across the interfaces of samples A and B are shown in Fig. 1. Minority-carrier diffusion lengths were computed at distances of multiple diffusion lengths away from the Schottky barrier to avoid errors due to surface recombination velocity.[14,16]

For an estimation of the recombination velocity at the regrowth interface the models of Zook,[11,12] Watanabe *et al.*,[12,13] and Ashley and Biard[14] were used. These models correlate the photogenerated current (I) with the distance across the barrier (z), the diffusion length of minority carriers (L), their diffusion coefficient (D), and absorption coefficient of the material (α). For our analysis the value of α was taken from Sturge[19] and a realistic value of D was taken as 5 $cm^2\,s^{-1}$ at room temperature.[14,18]

TABLE I. Recombination velocities at MBE GaAs regrown interfaces.

Reference number of model used	Recombination velocity at regrowth interface (cm/s) ($\times10^5$)	
	Sample A	Sample B
9	8.3	3.7
11	3.3	1.5
12	3.1	1.6

The values of L in the bulk regrown material and regrowth interface are found to be, respectively, 2.28 and 0.16 μm for sample A and 2.87 and 0.32 μm for sample B. The values of the recombination velocities obtained in these two samples by using the three different models are listed in Table I. The theoretical curves obtained by using Zook's model to fit the experimental data for samples A and B at the regrowth interface are shown in Fig. 2. $I(z)$ is the current near the interface and $I(\infty)$ is the current far away from the interface. The interface state densities, estimated from analysis of capacitance-voltage data[3] are 6.5×10^{11} and 1.2×10^{10} cm^{-2} in samples A and B, respectively. The measured value of the minority-carrier diffusion length in the regrown bulk GaAs[14,17,18] is of the order of 1–3 μm, which is common in most III-V bulk materials. However, the value of the parameter decreases by almost an order of magnitude at the regrowth interface. Such reduction in the diffusion length of minority carriers has also been observed at the heteroepitaxial strained interface between GaAs and GaP grown by liquid-phase epitaxy[18] and was interpreted to be due to the space-charge recombination at stacking faults and related defects. In our regrown samples, the reduction in diffusion length is probably caused by the disordered region at the interface, as discussed earlier.

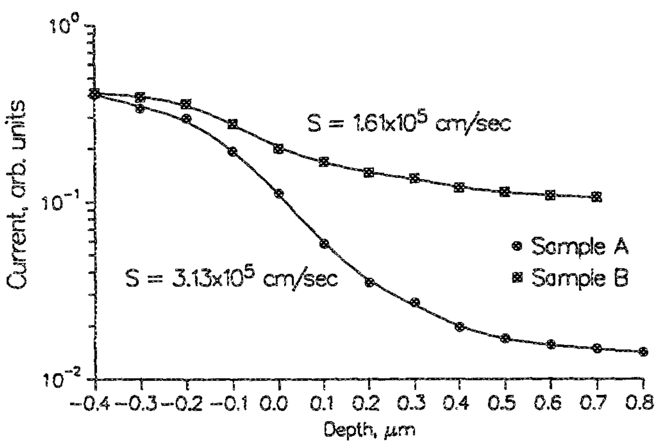

FIG. 1. Photogenerated current for light beam scan across the regrowth interface.

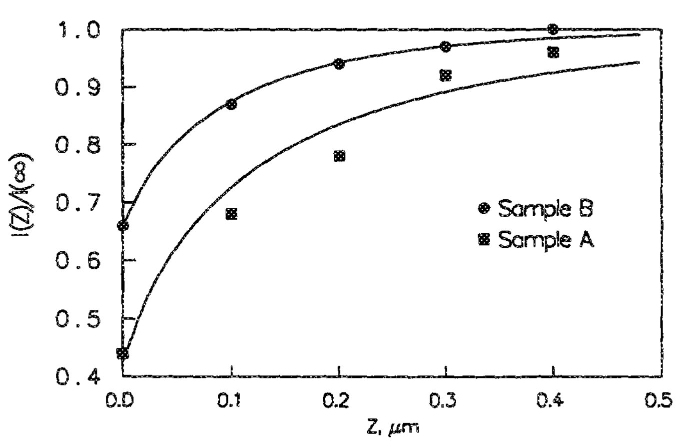

FIG. 2. Theoretical curves obtained from Zook's model to fit the experimental data near the regrowth interface.

The recombination velocity at the regrowth interface is found to be of the same order (2×10^5 cm/s) as the surface recombination velocity of n-type GaAs.[14] Zook's model, in comparison to the other two models, overestimates the surface recombination velocity, which was observed by Seager.[12] It has been observed by us[3] that the carrier depletion effect is much more pronounced in chemically etched regrowth interfaces, compared to that in ion-milled ones. Our results here are in agreement, as it is seen that the recombination velocity at the ion-milled regrowth interface is lower than that for the chemically etched one by a factor of two.

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