Ambipolar diffusion anisotropy induced by defects in *nipi*-doped $In_{0.2}Ga_{0.8}As/GaAs$ multiple quantum wells

D. H. Rich, K. Rammohan, Y. Tang, and H. T. Lin
Photonic Materials and Devices Laboratory, Department of Materials Science and Engineering, University of Southern California, Los Angeles, California 90089-0241

J. Maserjian and F. J. Grunthaner
Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

A. Larsson
Chalmers University of Technology, Department of Optoelectronics and Electrical Measurements, S-412 96 Göteborg, Sweden

S. I. Borenstain
Jerusalem College of Technology, Jerusalem, Israel 91160

(Received 26 August 1993; accepted for publication 17 November 1993)

The influence of strain-induced defects on the ambipolar diffusive transport of excess electrons and holes in the δ-doped InGaAs/GaAs multiple quantum well system has been examined with a new technique called electron-beam-induced absorption modulation (EBIA). The excess carrier lifetime and diffusion coefficient are obtained by a one-dimensional diffusion experiment that utilizes EBIA. An anisotropy in the ambipolar diffusion along both high-symmetry ⟨110⟩ directions is found, and this is seen to correlate with the distribution of dark line defects observed in cathodoluminescence.

The deleterious influence of defects on the transport properties in strained semiconductors is a topic of considerable interest owing to existing device applications in high-electron mobility transistors which are based on $In_xGa_{1-x}As/GaAs$ heterojunctions.[1] Likewise, photonic devices that rely on local changes in carrier density to achieve modulation of the optical properties are similarly affected by defects which can limit the lifetime of excess carriers and impede carrier transport.[2,3] Quantum heterostructures that exhibit strong photo-optic effects are required for *all-optical* spatial light modulators (SLMs) which are vital components for parallel all-optical computing and signal processing.

In this letter, we have employed a new technique called electron-beam-induced absorption modulation (EBIA) to examine the influence of strain-induced defects on the ambipolar diffusive transport of excess electrons and holes and the corresponding changes in the optical properties. The EBIA approach involves a *noncontact* scanning probe carrier injection and optical carrier transport measurement which is based on Shockley–Haynes type diffusion experiments.[3] Recently, we have shown that EBIA can be used as an imaging technique to determine the spatial distribution and orientation of defects that influence carrier transport in nipi-doped InGaAs/GaAs multiple quantum wells (MQWs).[3]

The periodic *nipi* doping of semiconductors ordinarily results in a large increase in the ambipolar diffusion coefficient as a result of the enhanced lifetime of the spatially separated electron-hole plasma and the strong space-charge-induced drift fields caused by the accumulation of majority carriers in the n- and p-type regions.[2–4] We demonstrate that EBIA can be used to measure this ambipolar diffusion coefficient and excess carrier lifetime, two parameters of fundamental importance describing the operation of opticallyaddressed SLMs. In addition, we demonstrate that an anisotropy in diffusive transport exists and this correlates with the difference in density of strain-induced defects along the high-symmetry ⟨110⟩ directions.

In EBIA, the excess carriers are generated by a high-energy electron beam within a scanning electron microscope (SEM).[3] A beam energy of 40 keV was used in this study. By utilizing the scanning capability of the SEM, spatial imaging information, in addition to spectral absorption variations can be obtained. The experimental setup utilizes a modified cathodoluminescence (CL) system to collect light which is transmitted through the MQW structure. An optical fiber is used to transmit light from a tungsten light source dispersed by a monochromator to the back side of the sample in the SEM vacuum chamber.[3] The absorption coefficient of light transmitted at an energy corresponding to the first quantized heavy hole-to-electron (hh1-e1) exciton transition depends on the density of excess carriers situated at the position of the optical fiber, as the electron-hole Coulomb interaction is screened by excess electrons in the MQW structure.[2,3] For excess carriers generated away from the optical fiber, the presence of intrinsic and extrinsic recombination channels will impede the diffusion of spatially separated carriers to the vicinity of the optical fiber. The diffusion coefficient and lifetime can be obtained by varying the sample temperature, modulating the electron beam source at variable frequencies, and measuring the corresponding modulation in the MQW absorption to study the carrier dynamics.

The sample was grown by molecular beam epitaxy, and consists of 44 $In_{0.2}Ga_{0.8}As$ QWs, each 65 Å wide, and separated by 780-Å-thick GaAs barriers. In the center of each GaAs barrier a p-type Be-doping plane with a sheet density of 9.0×10^{12} cm^{-2} was inserted. On both sides of the QWs, using 100-Å-thick spacer layers, n-type Si-doping planes with a sheet density of 3.0×10^{12} cm^{-2} were inserted. During electron-hole pair generation, electrons will be attracted to the QWs and the holes to the barrier region midway between

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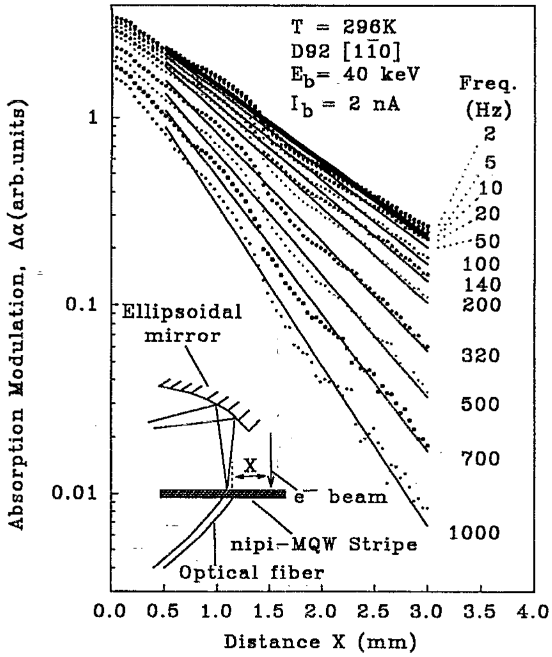

FIG. 1. Absorption modulation vs x, the distance from the center of the optical fiber, for various electron-beam blanking frequencies. The solid lines represent a linear fit to the data. The inset shows a schematic of the optical collection geometry relative to the electron probe position.

the wells, resulting in their spatial separation.[2,3] The sample was patterned into stripes 15 mm long with a $\sim$90-μm width along both [110] and [1$\bar{1}$0] directions using conventional lithography and chemical etching techniques. An important aspect of *nipi*-doped semiconductors is that passivation of the side edges of a mesa is not required to prevent surface recombination of excess carriers since the *majority* carriers (excess electrons and holes in the n- and p-type regions, respectively) are repelled from these edges. The optical fiber was placed near the center of the stripes and the relative absorption modulation was measured as a function of the electron-beam chopping frequency and the distance from the center of the fiber, as shown in the inset of Fig. 1. For each stripe, at all sample temperatures, the initial excess carrier density generated in the MQW at the point of excitation was kept constant at $\sim 2\times10^{10}$ cm^{-2} by varying the electron-beam current; this was determined by examining the absorption coefficient of the hh1-e1 exciton transition at $\lambda=948$ nm, for carrier generation directly above the optical fiber ($x=0$).[2,3] The stripe geometry allows excess carrier diffusion to occur in a quasi-one-dimensional manner; the time-dependent diffusion equation is given by

$$\frac{D_a\partial^2\Delta n(x,t)}{\partial x^2}-\tau^{-1}\Delta n(x,t)+G(x,t)=\frac{\partial\Delta n(x,t)}{\partial t}, \quad (1)$$

where $\Delta n(x,t)$ is the excess carrier density, D_a is the ambipolar diffusion constant, and τ is the intrinsic lifetime. The excess carrier generation rate, $G(x,t)$, can be approximated as $G(x,t)=\delta(x-x_0)[1+\cos(2\pi ft)]$ where x_0 is the position of the electron beam and f is the blanking frequency of the electron beam, and $\omega=2\pi f$. The excitation can be regarded as a δ-function source since the electron-beam interaction volume ($\sim\mu$m) is much less than the diffusion length ($\sim$mm). Equation (1) can be solved analytically using integration methods of Green's functions and Fourier transforms. The steady-state solution is approximated as follows:

$$\frac{\partial\Delta n(x,\omega)}{\partial t} \propto \frac{\omega\sin(\omega t)\exp[-x(1+\omega^2\tau^2)^{1/4}\cos(\theta/2)/(D_a\tau)^{1/2}]}{(1+\omega^2\tau^2)^{1/4}}, \quad (2)$$

where $\tan(\theta)=\omega\tau$. The absorption modulation $\Delta\alpha$ is approximately proportional to Δn for Δn less than the saturation excess carrier density of $\sim 1\times10^{11}$ cm^{-2}.[2] Thus, by creating a quasi-one-dimensional experiment (a long narrow strip of a sample so that diffusive transport takes place in only one direction) it will be possible to measure D_a and τ for a variety of excitation conditions and temperatures using conventional lock-in detection. A plot of $\ln(\Delta\alpha)$ vs x should produce a straight line with a slope equal to $(1+\omega^2\tau^2)^{1/4}\cos(\theta/2)/(D_a\tau)^{1/2}$. Figure 1 shows a plot of $\ln(\Delta\alpha)$ vs x for a line scan along the [1$\bar{1}$0]-oriented stripe. As expected, $\Delta\alpha$ decreases essentially in an exponential fashion with a frequency dependent slope for $x>\sim 0.5$ mm. The change in slope for $x<\sim 0.5$ mm is due to the finite width of the stripe which causes a two-dimensional diffusion in close proximity to the fiber. Small variations from linearity are observed in the form of steps, and this is consistent with the presence of an inhomogeneous distribution of defects previously imaged which act as barriers to the ambipolar diffusion.[3] These defect fluctuations have not been taken into account in the development of the simple model described by Eq. (1), and the D_a represents an effective diffusion constant weighted over a large distance.

A plot of the reciprocal slope vs electron-beam chopping frequency is shown in Fig. 2 for various temperatures. The solid lines represent nonlinear least-squares fits of the solution of Eq. (2) to the data while letting only two parameters, D_a and τ, vary during the fit. As the frequency approaches zero, the reciprocal slope becomes the ambipolar diffusion length $(D_a\tau)^{1/2}$, which is seen from the data in Fig. 3 to be greater than $\sim$1 mm for both ⟨110⟩ directions and temperatures studied here. The result of the fits is shown in Fig. 3, where D_a and τ are plotted as a function of $(kT)^{-1}$. Both D_a and τ exhibit an Arrhenius behavior which is indicative of thermal activation processes governing diffusive transport and recombination of spatially indirect electrons and holes, respectively.[2,3] The lifetime behavior is similar for the two directions since τ should not depend on the dimension or orientation of the diffusion experiment, and small variations may indicate inhomogeneities in sample quality. A linear fit to the lifetime data in Fig. 3(b) yields an activation energy of 127 meV. This is much smaller than the ideal modulation depth of $\sim$1.2 eV as strain induced defects are expected to lower the *nipi* barrier height.[2,3] A clear anisotropy in the transport exists for diffusion along the [110] and [1$\bar{1}$0] directions, as D_a is seen to vary exponentially from 29.8 to 12.3 cm^2/s along [110] and 13.8 to 0.21 cm^2/s along [1$\bar{1}$0] as the temperature is reduced from 340 to 163 K. The resulting

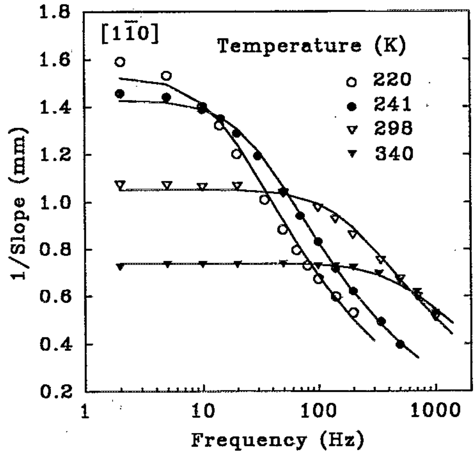

FIG. 2. The reciprocal slopes of the linear fits (as illustrated for some of the data in Fig. 1 vs the electron-beam blanking frequency for various substrate temperatures. The solid lines represent a nonlinear least-squares fit of the data to the solution of Eq. (2).

activation energies are 29 and 111 meV along the [110] and [1$\bar{1}$0] directions, respectively. Gulden *et al.* measured an enhanced ambipolar diffusion constant of 4600 cm^2/s for a non-strained *nipi*-doped GaAs structure using a contact-type Shockley–Haynes experiment.[4] This two orders of magnitude difference in diffusivity is certainly related to the existence of strain-induced defects.

The presence of defects is expected to impede the transport, as previously observed in EBIA,[3] by creating local potential fluctuations in the band edges. The difference in the activation energies suggest (i) the magnitude of the potential fluctuations or (ii) the density of such fluctuations differ along the [1$\bar{1}$0] and [110] directions. A monochromatic CL

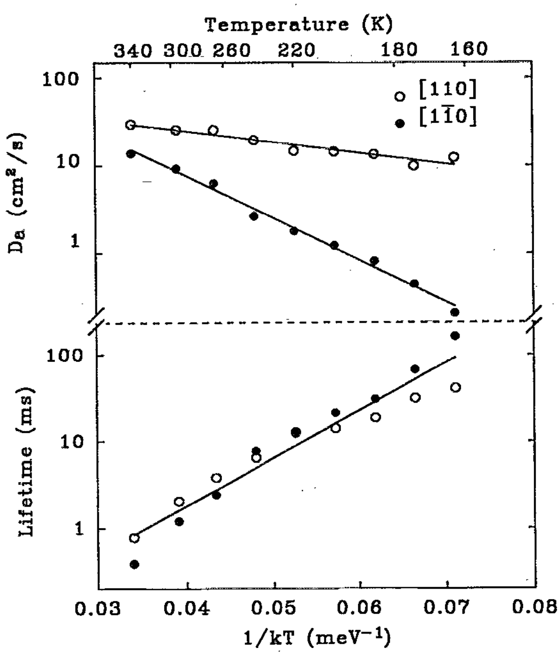

FIG. 3. The ambipolar diffusion coefficient D_a and lifetime τ vs $(kT)^{-1}$ for both ⟨110⟩ directions.

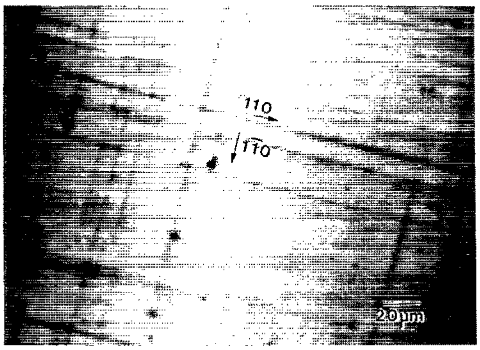

FIG. 4. A cathodoluminescence image taken for λ=946 nm, a 25-keV beam energy, and sample temperature of 84 K of the nipi-doped MQW sample.

image of the sample (λ=946 nm) is shown in Fig. 4. An asymmetry in the density of dark line defects is observed with densities of about 1.5×10^3 and 0.6×10^3 cm^{-1} seen under the present imaging conditions for the [1$\bar{1}$0] and [$\bar{1}$10] directions, respectively. This anisotropy has previously been attributed to the different levels of stress required to generate α and β misfit dislocation cores, and the differences in α and β dislocation propagation velocities.[5,6] In a previous CL study of $In_{0.2}Ga_{0.8}As$ MQWs having various periodicities and thicknesses, the presence of dark line defects were hypothesized to result from a distribution of point defects situated above interface misfit dislocations in the MQW.[7–9] The presence of such defects are expected to cause local potential fluctuations which could impede the diffusive transport and cause an increase in recombination rate.[3,7] Therefore, we conclude that the ambipolar diffusion anisotropy is caused by an enhanced density of potential fluctuations along [1$\bar{1}$0] relative to [110].

In conclusion, we have examined a *nipi*-doped $In_{0.2}Ga_{0.8}As$/GaAs MQW structure using EBIA, a *noncontact* technique involving optical and electron-beam probes to study the dynamics of the spatially separated electron-hole plasma. The diffusive transport is found to be limited by thermal activation across strain-induced potential fluctuations. An *anisotropy* in the excess carrier diffusive transport is found, and this is related to the asymmetry in the formation of strain-induced misfit dislocations.

This work was supported by grants from the USC James H. Zumberge Faculty Research and Innovation Fund.

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