Direct determination of the ambipolar diffusion length in strained $In_xGa_{1-x}As/InP$ quantum wells by cathodoluminescence

Robert B. Lee and Kerry J. Vahala
Department of Applied Physics, Mail Stop 128-95, California Institute of Technology, Pasadena, California 91125

Chung-En Zah and Rajaram Bhat
Bellcore, 331 Newman Springs Road, Red Bank, New Jersey 07701

(Received 21 December 1992; accepted for publication 15 March 1993)

The ambipolar diffusion length is measured in strained $In_xGa_{1-x}As/InP$ quantum wells for several mole fractions in the interval $0.3<x<0.8$ by cathodoluminescence. The ambipolar diffusion length is found to have a significantly higher value in the lower indium mole fraction samples corresponding to tensile-strained wells. This longer diffusion length for the tensile samples is consistent with results of carrier lifetime experiments by M. C. Wang, K. Kash, C. E. Zah, R. Bhat, and S. L. Chuang [Appl. Phys. Lett. **62**, 166 (1993)].

The transport properties of strained $In_xGa_{1-x}As/InP$ heterostructures are of interest due to their importance in optoelectronic devices. Pseudomorphic material has given semiconductor lasers new flexibility in operation wavelength as well as improvements in quantum efficiency. The heterostructure in this system is lattice matched to the InP substrate at an indium mole fraction of $x=0.53$ and the strain is tensile for $x<0.53$ and compressive for $x>0.53$. Here we present the direct determination of the ambipolar diffusion length in strained $In_xGa_{1-x}As/InP$ quantum wells by cathodoluminescence (CL) in a scanning electron microscope (SEM). This method is very straightforward due to the precision and ease with which the electron beam in the SEM can be controlled. The technique has been used previously on $Al_xGa_{1-x}As$ system by Zarem *et al.*[1,2]

The experiment is performed in a modified SEM with a fiber optic CL collection system as shown in Fig. 1. In the SEM, an energetic electron beam is incident upon the sample generating electron hole pairs. The sample is partly covered by a thin aluminum mask which prevents detection of luminescence emanating from the region under it, thus all detected luminescence is from radiative recombination occurring in the unmasked region. By generating carriers in the masked region and measuring the total luminescence power, $I(x)$, as a function of the distance of the *e*-beam from the mask edge, x, we are able to determine the diffusion length. The simplicity of the technique results from the fact that luminescence intensity depends exponentially on x/L_D when the *total power* is collected at the mask edge boundary.[3] In our experiments, a ~750-Å-thick aluminum mask consisting of 200 μm stripes separated by 50 μm is used. The electron-hole pairs are generated within the quantum well by a 20 kV electron beam. The *e*-beam position is varied from 5.4 to 1.6 μm from the mask edge in steps of 760 Å in five identical scans separated by 0.38 μm.

In Fig. 2 are depicted the structure of five $In_xGa_{1-x}As$ quantum-well samples used in the study: three tensile-strained samples with $x=0.3$, 0.41, 0.43, a lattice-matched sample with $x=0.53$, and a compressively strained sample with $x=0.8$. The layers indicated by "P-Q" and "Al-Q" are quaternaries of InGaAsP and AlInGaAs, respectively, lattice matched to the InP substrate. In Fig. 3 are shown the typical data runs of the diffusion length measurements on the five samples. All data were taken at room temperature at carrier densities in the range 10^{17}–10^{18} cm^{-3}. It was observed that the exposure to the electron beam altered the diffusion length. Thus, the beam was scanned toward the mask edge such that the material between the beam and the mask edge had not been altered by the electron beam. Although these precautions were taken, we found a distribution in the data points giving rise to deviations as high as 12% as summarized in Fig. 4. The diffusion length, however, does consistently decrease with the increase in the indium mole fraction leading to compressive strain.

The increase in the diffusion length for the smaller indium mole fraction samples may imply an increase in either mobility or lifetime since according to the Einstein relation $L_D=\sqrt{D\tau}=\sqrt{k_BT\mu\tau/q}$, where L_D, D, μ, and τ are the diffusion length, diffusivity, mobility, and carrier lifetime, and where k_B, T, and q are Boltzmann's constant, temperature, and the electron charge, respectively. Ambipolar mobility, however, is inversely proportional to the sum of the effective masses for both holes and electrons. Although the effective masses in the strained $In_xGa_{1-x}As$ system are not known precisely, it is known that compres-

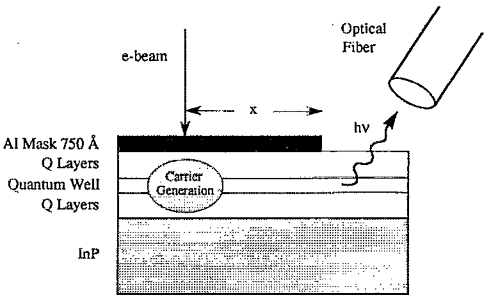

FIG. 1. Schematic diagram of the carrier diffusion length experiment. The electron beam incident on the sample generates electron-hole pairs whose luminescence upon recombination is collected by the optical fiber. The Al mask blocks detection of luminescence from the region under it (adapted from Ref. 1).

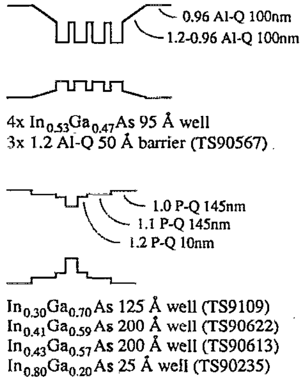

FIG. 2. A simplified depiction of the five quantum-well structures studied. The numbers preceding the P-Q or Al-Q indicate the approximate luminescence peak for the particular quaternary in micrometers.

sive biaxial strain results in a smaller in-plane effective mass and that highly tensile biaxial strain results in a larger in-plane effective mass for the holes.[4] Therefore, when the effective mass of the carriers is the only variable considered, the diffusion length for the compressive sample should be greater, in clear contradiction of the above experimental results.

This would indicate that the variable responsible for the significant difference in the carrier diffusion length may be τ or τ_c, the carrier scattering lifetime determining mobility. The experimental work of Wang *et al.*,[5] however, leads us to believe it is the former. The investigation of recombination in these structures indicates an approximately twofold increase in lifetime for similar structures of highly tensile-strained samples vs compressively strained samples. Furthermore, for a carrier density on the order of 10^{18} cm^{-3}, Auger recombination is shown to be less than 10% which would indicate that the diffusion length measured here is not significantly affected by Auger recombination.

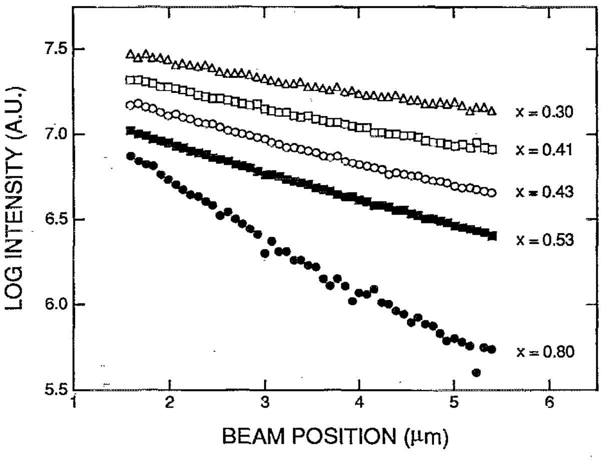

FIG. 3. Log of the cathodoluminescence intensity as a function of beam position for the five quantum wells. The ambipolar diffusion length is given by the reciprocal of the slope.

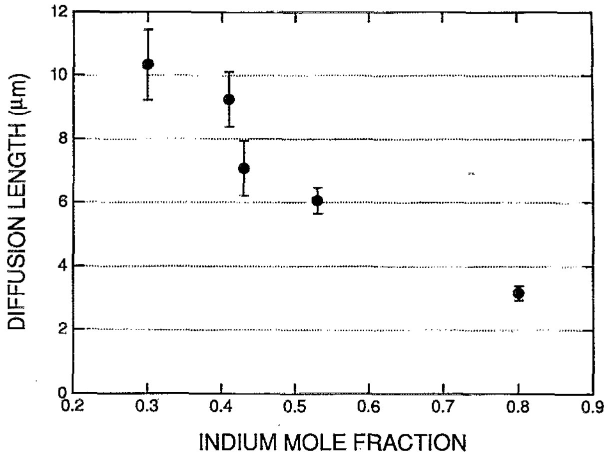

FIG. 4. Ambipolar diffusion length L_D in the five samples studied. The graph gives the average of the several measurements made on each sample and the standard deviation.

In conclusion, we have made a direct determination of the ambipolar diffusion length in five strained $In_xGa_{1-x}As/InP$ quantum well samples by cathodoluminescence in a scanning electron microscope. A significantly longer diffusion length was measured for the tensile-strained samples. This result seems to be in agreement with the experimental lifetime measurements of Wang *et al.*

The authors would like to acknowledge the support of the National Science Foundation. One of us (R.B.L.) would like to acknowledge the support of a National Defense Science and Engineering Graduate Fellowship.

[1] H. A. Zarem, P. C. Sercel, J. A. Lebens, L. E. Eng, A. Yariv, and K. J. Vahala, Appl. Phys. Lett. **55**, 1647 (1989).

[2] H. A. Zarem, J. A. Lebens, K. B. Nordstrom, P. C. Sercel, S. Sanders, L. E. Eng, A. Yariv, and K. J. Vahala, Appl. Phys. Lett. **55**, 2622 (1989).

[3] W. Vanm Roosbroeck, J. Appl. Phys. **26**, 380 (1955).

[4] M-P Houng and Y-C Chang, J. Appl. Phys. **65**, 4990 (1989).

[5] M. C. Wang, K. Kash, C. E. Zah, R. Bhat, and S. L. Chuang, Appl. Phys. Lett. **62**, 166 (1993).