Periodic $nipi$ doping of multiple quantum well (MQW) structures allows for the formation of a spatially separated electron-hole plasma, which can be excited by relatively weak external light or electron beams due to the large enhancement in the excess carrier lifetime. These structures exhibit large photo-optic effects which can be utilized for applications in all-optical spatial light modulators (SLMs) which are the building blocks of high-information throughput optical computing elements and Fourier-plane image processing devices. The InGaAs/GaAs MQW system, owing largely to the transparent nature of the GaAs substrate with respect to the MQW interband transition energies, is a leading candidate for the fabrication of SLMs. We demonstrate in this letter that the spatially separated electron-hole plasma can be used as a probe to study the MQW absorption modulation. The influence of structural defects on the diffusive transport of carriers is imaged with a $\mu$m-scale resolution.

Using a novel technique called electron beam-induced absorption modulation imaging (EBIA), we examine the influence of defects on the ambipolar diffusive transport in $nipi$-doped In$_{0.2}$Ga$_{0.8}$As/GaAs MQWs. In EBIA, the excess carriers are generated by a high-energy electron beam in a scanning electron microscope and used as a probe to study the MQW absorption modulation. The influence of structural defects on the diffusive transport of carriers is imaged with a $\mu$m-scale resolution.

The sample (designated D92) was grown by molecular beam epitaxy, and consists of 44 In$_{0.2}$Ga$_{0.8}$As QWs, each 65 $\AA$ wide, and separated by 780 $\AA$ thick GaAs barriers. In the center of each GaAs barrier a $p$-type Be-doping plane with a sheet density of $9.0 \times 10^{12}$ cm$^{-2}$ was inserted. On both sides of the QWs, using 100 $\AA$ thick spacer layers, $n$-type Si-doping planes with a sheet density of $3.0 \times 10^{12}$ cm$^{-2}$ were inserted. The $\delta$ doping causes a linear variation in the band edges along the growth direction, as shown in Fig. 1 (b). During electron-hole pair generation, electrons will be attracted to the QWs and the holes to the barrier region midway between the wells, resulting in their spatial separation. The recombination of the spatially separated carriers occurs through spatially indirect radiative tunneling recombination and spatially direct recombination of thermally excited carriers, as denoted schematically by the lifetimes $\tau_1$ and $\tau_2$, respectively, in Fig. 1(b).

Absorption spectra (solid lines) for various electron beam currents, $I_b$, are shown in Fig. 2 at a sample temperature of 115 K, and were obtained by chopping the monochromator probe. The effective QW absorption coefficients were calculated according to $(-L_d)^{1/2} I_T$, where $I_T$ is the measured normalized transmission through the sample and $L_d$ is the total thickness of the MQW structure. The total light power through the fiber was $\sim 10^{-7}$ W with a spectral resolution of 1 nm. The hh1-e1 exciton peak, which is located at $\lambda = 948$ nm, is seen to quench as the current level is increased; this is a result of the screening of the Coulomb interaction in the QWs by the electron.
Electron Beam-Induced Absorption Modulation (EBIA)

(a)

(b)

Band Diagram of InGaAs/GaAs MQW ndoped Sample

FIG. 1. Schematic of electron beam-induced absorption modulation imaging and cathodoluminescence setup in (a). Band diagram of a MQW nip structure showing spatial separation of electrons and holes which occurs under electron beam excitation (b). The structure is illustrated for the case of S doping, which results in linear variations in the conduction (EC) and valence (Ev) band edges relative to the quasi Fermi levels for electrons and holes ($\phi_e$ and $\phi_h$, respectively).

The differential absorption spectrum (dashed curve of Fig. 2) was obtained by chopping the electron beam, this enables an observation of the higher lying excitonic transitions. The quenching of the hhl-el exciton absorption coefficient in Fig. 2 is seen to depend approximately logarithmically on the beam current as expected from the reduction of the recombination lifetime with increasing carrier density.

A panchromatic CL image of the sample is shown in Fig. 3(a) with a 115 K temperature. The CL luminescence is primarily due to the MQW exciton associated with the e1-h1 transition. The dark line defects (DLDs) are oriented along the [110] and [110] directions, and they are a result of strain-induced interface misfit dislocations. Based on previous CL and transmission electron microscopy data, Rich and co-workers have proposed that a Cottrell atmosphere of point defects in the MQW region is responsible for the nonradiative recombination associated with the DLDs. It is possible to obtain spatial information concerning changes in the differential absorption by scanning the electron beam within the vicinity of the optical fiber center. An EBIA image [shown in Fig. 3(b) for $T=115$ K], was obtained by detecting the transmitted signal at $\lambda=948$ nm, corresponding to the e1-h1 exciton absorption. The electron beam ($I_b=1$ nA) was pulsed at a fixed frequency of 500 Hz while rastered in two dimensions across the sample to generate a 640x480 pixel image with the differential absorption intensity value stored in 1 byte of memory per pixel. The EBIA image of Fig. 3(b) shows the influence of structural defects on the diffusive transport of carriers with a $\mu$m-scale resolution. The center of the bright spot in Fig. 3(b) corresponds to the region of greatest excess carrier density and the region where the electron beam causes the largest transmission modulation, which is near the center of the optical fiber. A histogram of the imaging results of Fig. 3 is presented in Fig. 4. The curves illustrate the intensity versus electron beam position relative to the fiber center (distance=0) along the [110]-oriented line shown in Fig. 3(b) for CL, the absorption modulation $\Delta\alpha$, and its derivative $\partial\Delta\alpha/\partial x$. The center of the steps in $\Delta\alpha$ show up as peaks in the derivative scan. Vertical dotted lines are drawn in the figure to illustrate the strong correlation between dips and shoulders in the CL intensity at DLDs and the positions of the steps observed in the absorption modulation. These results demonstrate, remarkably, that the orientation and positions of steps seen in the absorption modulation correspond with the orientation and position of DLDs seen in the CL image. The transport of electrons and holes is, therefore, influenced by the presence of a Cottrell atmosphere of point defects which is well separated spatially from the interface misfit dislocations.

The presence of point defects lying in the regions delineated by the DLDs in CL imaging can influence the diffusion process in the following ways: (i) by creating diffusion barriers, (ii) by creating midgap recombination centers, and (iii) by affecting the lifetime of spatially indirect transitions. Point defects can create local variations in the band edges relative to the Fermi level, the depletion length will depend on the charge associated with the defect and the local dopant concentration. Since the electrons and holes in the plasma are confined to the n- and p-type regions, respectively [see Fig. 1(b)], a defect-induced change in the band edges will push the Fermi level (or quasi-Fermi level under excitation) closer to the middle of the gap. In case (i), this bandbending will cause the majority carriers to be repelled from the point defects and the Cottrell at-
mosphere of defects will act as a barrier to diffusion. A large excess carrier concentration will reduce the band bending, in a manner similar to the barrier reduction which occurs in a surface photovoltaic shift. In case (ii), the barrier reduction will result in an attendant increase in overlap between wave functions of the midgap defect states and the majority carriers. Also, thermally assisted defect-induced recombination of majority carriers can occur at high temperatures. This is similar to the existence of thermal activation barriers for minority carriers caused by defects in uniformly doped semiconductors which causes the enhancement of nonradiative recombination at high temperatures. In case (iii), a large density of point defects will increase the average value of the effective band gap $V_k$ [reduce the barrier height $\Delta E$ in Fig. 1(b)], resulting in a smaller value of $\tau_f$. While the three cases are not exhaustive, they illustrate possible ways in which a Cottrell atmosphere of defects can cause the measured steplike response in the EBLA image of Fig. 3(b).

Recent theoretical calculations by Jonsson et al. have shown that the lifetime for an ideal In$_{0.2}$Ga$_{0.8}$As/GaAs MQW nip-doped structure is several orders of magnitude longer than the lifetime measured by an optically induced absorption modulation technique. The primary cause suggested for this lifetime discrepancy was a spatial redistribution of dopants which would lead to an effective decrease in $\Delta E$, and thus increase in tunneling recombination and spatially direct recombination of thermally excited carriers. The present structure in the EBLA imaging results demonstrates that extrinsic defect related mechanisms can also affect the absorption modulation, excess carrier lifetime and carrier transport.

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