Influence of defects on electron–hole plasma recombination and transport in a nipi-doped In$_x$Ga$_{1-x}$As/GaAs multiple-quantum well structure

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(Received 18 July 1994; accepted for publication 17 February 1995)

The nonlinear optical and transport properties of a nipi-doped In$_x$Ga$_{1-x}$As/GaAs multiple-quantum well sample ($x=0.23$) has been studied using a novel approach called electron-beam-induced absorption modulation (EBIA). The absorption in the sample is modulated as a result of screening of the built-in electric field in the nipi structure due to excess carrier generation. The change in field causes a Stark shift of the first quantized optical transitions in QWs which are situated in the intrinsic layers. In EBIA, a scanning electron probe is used to locally generate an electron–hole plasma that is used to study the spatial distribution of defects that impede excess carrier transport and reduce the lifetime of spatially separated carriers. The Stark shift in the MQW structure is imaged with micrometer-scale resolution and is compared with cathodoluminescence imaging results which show dark line defects resulting from strain-induced misfit dislocations. Theoretical calculations using Airy functions in the transfer-matrix method with a self-consistent field approximation were used to determine the energy states, wave functions, and carrier recombination lifetimes of the MQW as a function of the built-in field. A quantitative phenomenological analysis is employed to determine the built-in field, excess carrier lifetime, and ambipolar diffusion coefficient as a function of the excitation density. The defects are found to create potential barriers and recombination centers which impede transport and markedly reduce the excess carrier lifetime. © 1995 American Institute of Physics.

I. INTRODUCTION

The development of materials exhibiting highly nonlinear optical properties is crucial for the development of spatial light modulators (SLMs), which modulate both spatially and temporally the intensity, phase, or polarization of optical beams. SLMs are the building blocks of high-information throughput optical computing and communication elements. The spatially separated electron–hole ($e–h$) plasma that can be generated in periodically doped nipi multiple-quantum well (MQW) structures exhibits novel nonlinear optical properties which can be utilized for applications in SLMs. SLMs that are based on the strained In$_x$Ga$_{1-x}$As/GaAs MQW system are a prime candidate for incorporation into information processing systems, owing largely to the transparent nature of the GaAs substrate relative to the MQW excitonic energy. The incorporation of nipi-doped MQWs into an asymmetric Fabry–Perot cavity has recently demonstrated the feasibility of high-contrast optically addressed SLMs. When designing the nipi-doped MQW structure so that the QWs are located in the intrinsic region, the generation of excess carriers will screen the built-in electric field caused by the doping and induce a blue shift in the MQW excitonic absorption by reducing the quantum-confined Stark effect (QCE).

In order to maximize the exciton peak energy shifts associated with the QCSE, the nipi-doped MQW structure must be designed to maximize the built-in field and allow for the generation of large free-excess carrier concentrations which can screen the field. The presence of strain-induced misfit dislocations and point defects in nipi-doped In$_x$Ga$_{1-x}$As/GaAs MQWs can reduce the excess carrier lifetime and impede ambipolar diffusive transport of carriers. Consequently, the photo-optic sensitivity of the SLM to external write beams is potentially reduced. Although a long recombination lifetime in the nipi structures generally limits the SLM recovery rate for all-optical addressing to the kilohertz range, pixelated interconnect arrays, e.g., 1000×1000, would allow for a large data throughput in the gigabits/second range. It is apparent that the performance tradeoffs of speed and sensitivity in nipi-doped MQWs are determined by the carrier lifetime. Therefore it is of paramount importance to study the influence of the nipi MQW structural properties on carrier transport and the excess carrier lifetime.

Previously, we have shown that a new imaging technique called electron-beam-induced absorption modulation (EBIA) can be employed to study the electron–hole carrier dynamics and influence of defects on $e–h$ plasma transport in nipi-doped MQW structures with a micrometer-scale spatial resolution. In order to achieve the high spatial resolution and controllability of depth of excitation, a high-energy elec-
tron beam in a scanning electron microscope (SEM) is used to generate locally an electron–hole plasma. The built-in electric field caused by nipi doping acts to spatially separate the carriers, resulting in large excess carrier lifetimes that are typically on the order of \( \sim 10^{-7} \) ms.\(^{14,15}\) A local generation of excess electrons and holes will act locally to screen the built-in field and increase the effective nipi band gap, resulting in large in-plane drift fields of opposite sign in adjacent n- and p-type layers. The ensuing drift of excess electrons and holes is in a direction away from the source of excitation and is driven by the in-plane gradient of the electron and hole quasi-Fermi levels.\(^{11,16}\) This results in a large enhancement of the ambipolar diffusion constant relative to bulk semiconductors.\(^{11,16}\) The structure previously examined with EBIA enabled absorption modulation through quenching of the exciton resonance by state filling and screening of the \( e^{-} h^{+} \) Coulombic interaction in MQWs.\(^{13-15}\)

In this paper, we have examined a sample in a class of nipi-doped MQWs which utilizes the QCSE for light modulation.\(^{7,9}\) We have used EBIA imaging and spectroscopy toward studying spatial variations in the QCSE that are caused by strain-induced defects in a nipi-doped MQW structure. The presence of dislocations and point defects in MQWs can act to impede \( e^{-} h^{+} \) plasma transport and create spatial inhomogeneities in the built-in electric field during excitation. We show that the anisotropy in ambipolar diffusive transport, induced by the defects, can be visualized directly by performing EBIA imaging of the QCSE. The EBIA imaging further reveals here, with micrometer-scale resolution, the influence of defects on absorption modulation and ambipolar diffusive transport. Theoretical calculations using Airy functions in the transfer-matrix method (TMM)\(^{17-19}\) with a self-consistent field approximation were used to determine the energy states, wave functions, and carrier recombination lifetimes of the MQW as a function of electric field. A quantitative phenomenological analysis is employed to determine the built-in field, excess carrier lifetime, and ambipolar diffusion coefficient as a function of the excitation density, all of which are quantities of fundamental importance in describing nonlinear optical properties of nipi-doped structures. The present EBIA experiment involves a novel approach using a comparison of patterned and unpatterned nipi-doped MQW samples to determine the ambipolar diffusion length as a function of the built-in field. Calculations of the lifetime and ambipolar diffusion coefficient are compared with experiment to assess the influence of strain-induced defects on the excess carrier recombination and transport dynamics.

II. EXPERIMENT

The nipi-doped MQW structure was grown by molecular-beam epitaxy on an undoped GaAs(001) substrate. Six periods of the nipi structure, schematically illustrated in Fig. 1, were grown. The substrate temperature was maintained at \( \sim 500 \) °C. A \( \delta \)-doping approach was employed for nipi doping. By localizing the dopants in planes, a deeper and more uniform modulation of the conduction- and valence-band potentials relative to the Fermi level can be achieved as a result of minimizing the statistical spread of the dopants.\(^{8-10}\) The Si and Be impurities are localized within a few atomic layers in the corresponding n- and p-doping planes, respectively. The sheet doping densities used for both n- and p-type planes is \( \times 10^{12} \) cm\(^{-2}\) and the distance between the doping planes is \( 1000 \) Å. The MQW structure was centered between doping planes and is comprised of four \( \text{In}_{x} \text{Ga}_{1-x} \text{As} \) QWs with nominal composition \( x=0.23 \), each \( 65 \) Å thick, and separated by \( 100-\)Å-thick GaAs barriers. The structure was capped with \( 1000 \) Å of undoped GaAs. In order to laterally confine the electron–hole plasma to a well-defined region (as will be discussed in Sec. IV) conventional lithographic techniques were used to pattern the sample into square mesas of \( \sim 90 \mu m \times 90 \mu m \). A nonpatterned planar region of \( \sim 1 \) cm\(^{-2}\) was examined to study the effects of defects on the ambipolar diffusion of carriers.

In EBIA, the electron–hole plasma is locally generated by the high-energy beam (30 keV) in a modified JEOL 840A-SEM. Details of the experimental technique have been previously reported.\(^{13-15}\) Briefly, a multimode optical fiber with a \( 100 \) μm core diameter is used to transmit light from a tungsten light source dispersed by a \( 0.25 \) μm monochromator to the backside of the sample. The total light power through the fiber was \( \sim 10^{-7} \) W with a spectral resolution of 1 nm. Measurements using various other powers confirmed that self-electro-optic device effects were negligible. The optical fiber was placed near the center of the patterned mesa. An ellipsoidal mirror, also used for the optical collection in cathodoluminescence (CL), collects the light transmitted through the MQW structure while the electron beam is rastered in the vicinity of the fiber position. The light is coupled out of the SEM vacuum chamber by a separate optical fiber bundle where it is detected by a Si photodetector, as roughly illustrated in Fig. 1. The technique utilizes lock-in detection by chopping either the light source from the monochromator or blanking the electron-beam source. The images reveal a
contrast in the absorption modulation caused by the influence of intrinsic and extrinsic recombination channels on the diffusion of spatially separated carriers to the vicinity of the optical fiber. Lifetime effects and recombination centers are examined by varying the sample temperature and by modulating the electron-beam source to study the \( e - h \) plasma transport dynamics.

III. THEORY

A. Calculation of energy levels and wave functions using Airy functions in the TMM

The growth of an In\(_{x}\)Ga\(_{1-x}\)As/GaAs MQW on GaAs(001) results in an alternating biaxial in-plane compression and tension in the In\(_{x}\)Ga\(_{1-x}\)As and GaAs layers, respectively. This results in an increase and decrease in band gap in the In\(_{x}\)Ga\(_{1-x}\)As and GaAs layers, respectively, and splitting of the heavy-hole (hh) and light-hole (lh) bands in opposite directions. The unstrained In\(_{x}\)Ga\(_{1-x}\)As band gap as a function of composition \( x \) at room temperature is

\[
E_g(x) = 1.424 - 1.615x + 0.555x^2.
\]

(1)

The strain-induced change of the hh and lh bands is given by

\[
\Delta E_{i} = \left[ -2a(x) \frac{C_{11}(x) - C_{12}(x)}{C_{11}(x)} + b(x) \frac{C_{11}(x) + 2C_{12}(x)}{C_{11}(x)} \right] \varepsilon_i(x),
\]

(2)

where the + and − signs refer to the strain-split bands and \( i \) is an index that refers either to the In\(_{x}\)Ga\(_{1-x}\)As or GaAs layers. A minimization of the total elastic energy for an arbitrary superlattice with alternating layers of materials 1 and 2 (i.e., GaAs and In\(_{x}\)Ga\(_{1-x}\)As) yields an in-plane lattice constant \( a_{x,y} \), such that

\[
a_{x,y} = a_{1}d_{1}\xi_{1} + a_{2}d_{2}\xi_{2}.
\]

(3)

where \( \xi_{i} = (C_{11} + C_{12} - 2C_{12}'/C_{11})^{-1} \), \( a_{i} \) is the unstrained lattice constant, \( d_{i} \) is the effective thickness, and the subscripts \( i = 1,2 \) refer to GaAs and In\(_{x}\)Ga\(_{1-x}\)As layers, respectively. The in-plane strain \( \varepsilon_{i}(x) \) is ideally given by

\[
\varepsilon_i = \frac{a_{x,y} - a_{i}}{a_{i}}.
\]

(4)

The presence of a high density (greater than \( \sim 10^{4} \text{ cm}^{-1} \)) of dark line defects which are observed in the CL imaging (see Sec. IV B) suggests that a considerable relaxation of the MQW structure with respect to the substrate occurs, and we assume that the remaining strain has a negligible effect on the determination of \( \varepsilon_{i}(x) \) and \( \Delta E_{i} \).

The hydrostatic deformation potential \( a(x) \) and uniaxial deformation potential \( b(x) \) are given by \( a(x) = -8.70 + 3.00x - 0.23x^2 \) and \( b(x) = -1.7 - 0.1x \) (in electron volts).\(^{23}\) The elastic constants \( C_{11}(x) \) and \( C_{12}(x) \) are given by \( C_{11}(x) = (11.88 - 3.551x)10^{11} \) and \( C_{12}(x) = (5.38 - 0.854x)10^{11} \) (in dyn/cm²).\(^{24}\) The conduction- to valence-band offset ratio (\( \Delta E_{c}/\Delta E_{v} \)) is taken as 70/30, and is assumed independent of \( x \).\(^{24}\)

The solutions \( \psi_{n}(z) \) and \( E_{n} \) to the Schrödinger equation for a particle subject to an electric field \( (\vec{F}) \) involve linear combinations of Airy functions \( Ai(z) \) and \( Bi(z) \).\(^{17-19}\) Using Airy functions in the TMM, we have calculated the eigenstates as a function of the electric field for the sample whose structure is depicted in Fig. 1. In the TMM, briefly, continuity conditions for \( \psi_{n} \) and \( mk^{-1} d\psi_{n}/dz \) at the ith-layer interfaces are used to construct a \( 2 \times 2 \) iteration matrix for each In\(_{x}\)Ga\(_{1-x}\)As/GaAs interface from which the coefficients of the Airy functions in each layer are determined\(^{17,18}\). In order to accurately determine the potential profile, strain-induced effects described in Eqs. (1)–(4) must be taken into account. The boundaries of the potential profile, \( V_{0}(z) \), are defined such that \( V_{0}(z) = 0 \) at \( z = 0 \) and \( V_{0}(z) = |e\vec{F}F'/2| \) for \( |z| \geq P/2 \), where \( P \) is the nip period (\( P = 2000 \text{ Å} \) here) and \( F \) is the electric field. This potential profile allows for each bound-state wave function to be normalized which is a necessary condition for the lifetime calculation in Sec. III B. The effective masses in the quantum wells and barriers are taken as a linearization between those in GaAs and InAs and are \( m_{e} = (0.0665 - 0.0435x)m_{0}, \) \( m_{lh} = (0.34 + 0.06x)m_{0}, \) and \( m_{lh} = (0.094 - 0.067x)m_{0} \), where \( m_{0} \) is the rest mass of the electron. The exciton binding-energy dependence on the field is small and is assumed to be a constant in the calculation.\(^{25}\) The energy states and wave functions are determined in the TMM by finding the energies necessary to force the coefficients of the unbound Airy functions to approach zero at the boundaries of one period of the nip-doped structure.

The results of the calculations are shown in Figs. 2 and 3 for electrons, and heavy and light holes. The electric field was fixed at 55.3 kV/cm for the wave functions and energies displayed in Fig. 2. The coupling of nearly degenerate states from QWs experiencing opposite fields results in four pairs of symmetric and antisymmetric wave functions for electrons and heavy holes localized in the QWs, as shown in Fig. 2. The splitting of these coupled QW states is small and is less than \( \sim 10^{-3} \text{ meV} \) for the present calculation shown. The dependence of the energy of confined states on electric field are shown in Fig. 3. The strain-induced modification of the hh band edge results in only a slightly attractive light-hole potential barrier of \( \sim 1.7 \text{ meV} \) which can not lead to light-hole localization in the QWs under any appreciable field; thus the light-hole potential resembles a simple V shape. The energy values for states localized in (i) the V-shaped GaAs barrier and (ii) the In\(_{x}\)Ga\(_{1-x}\)As QWs are shown in Fig. 3. A distinction between these two types of localization is observed, as field changes will shift the states localized in the V-shaped potential by modifying the slope of the barrier whereas the shift in states localized in the QWs occurs via the formation of a Stark ladder.\(^{26}\) The Stark ladder appears as a nearly linear shift in energy with field in Fig. 3 along four doubly degenerate energy lines from the \( e1, hh1, \) and \( hh2 \) states at \( F = 0 \). Energy eigenvalues along these four lines represent
nearly doubly degenerate states that are represented by symmetric and antisymmetric wave functions. A noncrossing behavior appears between states localized in QWs and the V-shaped barrier as a result of additional mixing of these states close to degeneracy. Dashed circles are illustrated in Fig. 3 for the lowest electron and hole QW states involved in the noncrossing. The larger mass of heavy holes relative to electrons results in more hh states confined to the V-shaped barrier as indicated in Figs. 2 and 3. For the case of light holes, only states confined to the V shape are found.
B. Calculation of excess carrier lifetime

The calculation of the electron and hole eigenstates is necessary for a theoretical calculation of the excess carrier lifetime. The transition rate for recombination of excess carriers is given by Fermi's golden rule and is proportional to a weighted sum of the squares of the overlap integrals between electron and hole wave functions. The theoretical recombination lifetime \( \tau_{th} \) is given by

\[
\frac{1}{\tau_{th}} = \sum_{k=1}^{s_e} \frac{N_e(k)}{N_T P_T} \left( \frac{s_{hh}}{\tau_r(k,m)} + \sum_{j=1}^{s_h} \frac{s_{hh}}{\tau_r(k,j)} \right),
\]

where \( N_T \) and \( P_T \) are total steady-state free-electron and hole sheet densities, respectively, occurring mainly from excitation. The reduced recombination rate \( 1/\tau_r(k,m) \) between electron in state \( k \) (\( \psi_k^e \)) and heavy hole or light hole in state \( m \) (\( \psi_m^h \)) is given by

\[
\frac{1}{\tau_r(k,m)} = \frac{1}{\tau_{dir}} \left( \int_{-\infty}^{\infty} dz \, \psi_k^e(z) \psi_m^h(z) \right)^2,
\]

where \( \tau_{dir} = 10 \text{ ns} \). The number of energy states considered in the calculations for electrons, heavy holes, and light holes are labeled as \( S_e \), \( S_{hh} \), and \( S_h \). The electron, heavy-hole, and light-hole eigenstates [labeled \( N_e(i) \), \( P_{hh}(i) \), and \( P_{lh}(i) \), respectively] are determined by integrating the product of the Fermi function and the 2D density of states and are given by

\[
N_e(i) = \frac{4 \pi m_e}{\hbar^2} \left[ kT \ln \left( 1 + \exp \left( \frac{E_i - \phi_n}{kT} \right) \right) - E_i + \phi_n \right]
\]

and

\[
P_{hh,lh}(i) = \frac{4 \pi m_{hh,lh}}{\hbar^2} \left( kT \ln \left( 1 + \exp \left( \frac{\phi_p - E_i}{kT} \right) \right) - \phi_p + E_i \right),
\]

where \( \phi_n \) and \( \phi_p \) are the quasi-Fermi levels for electrons and holes and \( T \) is the temperature. The quasi-Fermi levels can be computed numerically once \( N_T \) and \( P_T \) are known by the following relations:

\[
N_T = \sum_{i=1}^{s_e} N_e(i)
\]

and

\[
P_T = \sum_{i=1}^{s_{hh}} P_{hh}(i) + \sum_{i=1}^{s_h} P_{lh}(i).
\]

The built-in field \( F \) for \( \delta \)-doped nipi structures varies linearly with excess carrier density (number per cm\(^2\)), \( \delta n_q \), and is given by

\[
F = F_0 - \frac{e \delta n_q}{2 \epsilon},
\]

where \( e \) is the electric charge, \( \epsilon \) the permittivity of the material, and \( F_0 \) the maximum built-in field which occurs when there is no excitation. In the present sample, the nearly equal densities of donors and acceptors results in a compensated semiconductor where the Fermi level is near midgap.

Upon excitation, the quasi-Fermi levels will split such that \( N_T = P_T = \delta n_q \). Using the results of the TMM calculations and Eqs. (5)–(11), we have calculated \( \tau_{th} \) as a function of the excess carrier density as shown in Fig. 4. In order to obtain convergence of \( \tau_{th} \) a large number of states must be employed, and the results shown are for \( S_e = 35, S_{hh} = 50, \) and \( S_h = 20 \). Electron and heavy-hole states localized in the QWs are found to contribute significantly to the sum in Eq. (5) as a result of a marked enhancement in overlap of wave functions, despite the reduced probability of occupation due to a larger energy separation from quasi-Fermi levels. For all states, the relative contribution to \( \tau_{th} \) involves an interplay between wave-function overlap and occupation probability. In order to assess the influence of the QWs on the overlap, a lifetime calculation, denoted as \( \tau_R \), was performed for a reference structure in which In\(_{x}\)Ga\(_{(1-x)}\)As QWs are absent (i.e., only a nipi-doped GaAs lattice is assumed). The results, shown in Fig. 4, demonstrate that inclusion of In\(_{x}\)Ga\(_{(1-x)}\)As QWs in this structure will enhance the overlap integrals to an extent where \( \tau_{th} \) is reduced by \(~4\) orders of magnitude relative to \( \tau_R \) at high fields.

C. Hartree corrections to the field and lifetime calculations

In a more rigorous calculation of the band profile, wave functions, and carrier lifetime, the influence of the carrier charge on the potential profile, \( V(z) \), must be calculated self-consistently. The dominant contribution in a self-consistent field calculation for nipi structures is the Hartree term

\[
V_H(z),
\]

where

\[
\frac{\partial^2 V_H(z)}{\partial z^2} = \frac{e}{\epsilon} \left[ \rho_e(z) + \rho_{hh}(z) + \rho_{lh}(z) \right]
\]

FIG. 4. The calculated and measured lifetimes vs. the electric field and the excess carrier density. The calculated reference lifetime (\( \tau_R \)) without QWs in the structure, the theoretical lifetime (\( \tau_{th} \)), the lifetime obtained from the phenomenological model (\( \tau_{ph} \)), and the lifetime obtained from the 3 dB cutoff frequency (\( \tau_{3dB} \)) are shown.
and the average three-dimensional charge densities of heavy holes, light holes, and electrons \( \rho_{hh}(z) \), \( \rho_{lh}(z) \), and \( \rho_e(z) \), respectively] are given by

\[
\rho_{hh}(z) = e \sum_{i=1}^{s_h} P_{hh}(i) |\psi_{lh}^i(z)|^2,
\]

\[
\rho_{lh}(z) = e \sum_{i=1}^{s_l} P_{lh}(i) |\psi_{lh}^i(z)|^2,
\]

\[
\rho_e(z) = -e \sum_{i=1}^{s_e} N_e(i) |\psi_e^i(z)|^2.
\]

The integration of this Poisson's equation is subject to the boundary conditions of \( \frac{\partial V_H(z)}{\partial z} = 0 \) and \( V_H(z) = 0 \) at \( z = 0 \). The self-consistent potential profile is written

\[
V(z) = V_0(z) + \frac{e}{e} \int_0^z dz' \int_0^{z'} dz'' (\rho_{hh}(z'') + \rho_{lh}(z'')) + \rho_e(z''),
\]

where \( V_0(z) \) is the potential profile of the nipi-doped MQW assuming a constant electric field as previously discussed. The wave functions and potential were calculated self-consistently using Airy functions in the TMM according to Eqs. (13) and (14) by discretizing the MQW potential into 90 intervals for one nipi period. The potential in each interval was linearized and approximated with a constant electric field; the use of more than 90 intervals did not alter appreciably the calculated lifetimes. A series of iterations were performed until \( V(z) \) converged. From the new self-consistent electron and hole wave functions, the calculated lifetimes were determined, as outlined in Sec. III B, and are plotted in Fig. 4. The calculated lifetimes for the nipi MQW and reference structure, using the Hartree corrections, are labeled with the sc subscript as \( \tau_{hh(sc)} \) and \( \tau_{R(sc)} \), respectively, and are plotted versus the excess carrier density. The electric-field axis, with respect to these calculations, refers to the approximate average field halfway between the \( n \)- and \( p \)-type \( \delta \)-doping layers.

The calculated self-consistent potential profile and charge densities for electrons and holes near respective \( n \)- and \( p \)-type regions are shown in Fig. 5 for three excess carrier densities of \( 7.5 \times 10^{10} \), \( 6.1 \times 10^{11} \), and \( 1.2 \times 10^{12} \) \( \text{cm}^{-2} \). It is apparent that the inclusion of the Hartree terms will tend to result in an increase in the electric field locally near the \( n \)- and \( p \)-type \( \delta \)-doped regions, resulting in the cusp-shaped potential near the \( \delta \)-doped regions. The spreading of the charge density along the \( z \) direction due to the finite spread of the wave functions will now result in a reduction in the excess carrier-induced screening of the depleted \( \delta \)-doped regions, compared to the case of a constant field as treated in Sec. III B, where an approximation of a two-dimensional excess carrier localization at the \( \delta \)-doping planes is assumed [as in Eq. (11)]. The local increase in the field also causes the wave functions to become less extended along the \( z \) direction, thereby reducing the electron–hole overlap integrals and increasing the excess carrier lifetime. At high excitation densities greater than \( 1 \times 10^{12} \) \( \text{cm}^{-2} \), the lifetimes \( \tau_{hh(sc)} \) and

\( \tau_{R(sc)} \) will begin to deviate significantly from the values of \( \tau_h \) and \( \tau_R \) obtained from the uncorrected fields. This is due to the presence of the finite cusp in the confining potential at the \( \delta \)-doped planes, which will act to reduce the wavefunction overlap integrals. For low excitation densities of \( \sim 1 \times 10^{11} \) \( \text{cm}^{-2} \), the increase in lifetime, however, is a relatively small effect, as observed in Fig. 4, with a less than \( 5\% \) increase in lifetime for the smallest carrier densities shown. The large spatial separation of carriers is still the dominant effect in causing the extremely long carrier lifetimes. The approximation of a constant field which varies
FIG. 6. EBIA absorption ($\alpha$) and differential absorption ($\Delta\alpha$) spectra for the planar region. The change in the quantum confined Stark effect is observed as the $h_{1-\epsilon_1}$ transition energy shifts to higher energies as the beam current ($I_b$) increases, indicating the built-in electric field reduces. A reduction in the field-induced broadening of the $h_{1-\epsilon_1}$ excitonic transition can be observed for higher beam currents. The EBIA absorption spectra for $I_b=0$ and $I_b=0.01$ nA in the upper panel nearly overlap, resulting in the appearance of a single spectrum.

linearly with carrier density [Eq. (11)] is evidently useful and valid for $\delta n_e=1\times10^{12}$ cm$^{-2}$, and will be used in developing a phenomenological model to determine the field as a function of carrier density in Sec. IV C.

IV. RESULTS AND DISCUSSION

A. Electron-beam-induced changes in the Stark shift

Room-temperature EBIA spectra for various electron-beam currents ($I_b$) are shown in Fig. 6 for the large mesa, and were obtained by chopping the tungsten light source at the entrance slit of the monochromator. The effective QW absorption coefficients $\alpha$ were calculated according to $\alpha=-L_{\text{eff}} \ln T$, where $T$ is the normalized transmission through the sample and $L_{\text{eff}}$ is the total thickness of the MQW structure. The peak of the absorption spectrum is the $n=1$ heavy-hole to electron ($h_{1-\epsilon_1}$) excitonic transition. A QCSE occurs here as a result of the field-induced change in quantized electron and hole energy levels. With increased beam current, the transition energy shifts toward shorter wavelengths, indicating that the built-in electric field $F$ experienced by the MQWs decreases due to screening of charge in the doping planes by the accumulation of excess carriers. For higher fields (reduced currents) the excitonic resonance broadens and its peak strength is reduced due to a reduced overlap of electron and hole QW wave functions and an increased field-induced tunneling rate of carriers out of the QWs.

The differential absorption $\Delta\alpha$ in Fig. 6 was obtained by chopping the electron probe at a low frequency of 5 Hz while keeping the monochromator source unchopped. The differential absorption spectra are required to determine the excitonic peak positions for the case of the small mesas since the transmitted light from the optical fiber generates an effective sampling area greater than the mesa size. Thus differential absorption automatically subtracts the effects of light transmitted through surrounding mesas since excess carriers that are generated by the pulsed electron beam are confined by the patterning. Figure 7 shows the wavelength of the peak position as a function of $I_b$ for both $\alpha$ and $\Delta\alpha$ measurements in the planar sample. The peak in the $\alpha$ spectrum is the $h_{1-\epsilon_1}$ excitonic peak position while the maximum and minimum values in the $\Delta\alpha$ spectrum represent two different excitonic extrema due to the subtraction of beam-on and beam-off absorption spectra. The inset of Fig. 7 shows a polynomial fitting of the $\alpha$ vs $\Delta\alpha$ peak positions in the planar region. This empirical curve facilitates a determination of the $h_{1-\epsilon_1}$ excitonic peak positions for EBIA in the patterned regions using the measured $\Delta\alpha$ data of the patterned regions.

B. EBIA imaging of the QCSE

EBIA images were obtained by rastering the electron beam in the vicinity of the optical fiber. The contrast in electroabsorption reveals the influence of defects on the ambipolar diffusive transport of carriers to the center of the optical fiber. Two types of EBIA images, at a temperature of 86 K, are shown in Figs. 8(a) and 8(b). A beam energy of 30 keV and current of 0.3 nA were used. The image of Fig. 8(a) represents the integrated intensity of all positive $\Delta\alpha$, in the range from 955 Å to 975 nm, as a function of electron-beam position (x,y). This was accomplished by summing 22 discrete monochromatic EBIA images from 955 to 975 nm.
clear contrast due to the strain-induced misfit dislocation formation is observed. The region of greatest intensity (white) corresponds to the position of the fiber where \( \Delta \alpha \) is the largest. Rectangularly shaped steps in the \( \Delta \alpha \) image correlate with the position and orientation of the DLD pattern imaged in the panchromatic CL image of the same region in Fig. 8(c). A new type of EBIA image is displayed in Fig. 8(b) in which the grey scale key represents a wavelength mapping of the spatial distribution of the high-energy \( \Delta \alpha \) peak position. The peak in \( \Delta \alpha \) was determined from a 22-point local EBIA \( \Delta \alpha \) spectrum for each of the 640×480 discrete \((x,y)\) positions in the image. This was enabled by acquiring and processing 22 discrete monochromatic EBIA \( \Delta \alpha \) intensity images in the range \( 595 \leq \lambda \leq 975 \) nm. The image clearly reveals the spatial distribution of the QCSE. When the electron beam is positioned at the optical fiber center, the reduction in the built-in field is the greatest, resulting in the largest blue shift (high-energy shift relative to the unexcited sample) of the

**FIG. 8.** EBIA and CL images of the planar region at \( T=86 \) K. An EBIA image showing the integrated values of positive \( \Delta \alpha \) in the range \( 955 \leq \lambda \leq 975 \) nm is shown in (a). A new type of EBIA image is displayed in (b) in which the grey scale key represents a wavelength mapping of the spatial distribution of the high-energy \( \Delta \alpha \) peak position. The CL image in (c) shows the DLD network caused by the formation of misfit dislocations.

**FIG. 9.** Histograms of EBIA and CL of the imaging data at \( T=86 \) K. The local minima (DLDs) in the CL intensity vs distance line scan are seen to correlate with the positions of steps in \( \Delta \alpha \), peaks in its derivative \( \partial \Delta \alpha / \partial x \), and shifts in the \( e1 hh1 \) wavelength scan [see Fig. 8(b)]. These results indicate that strain-induced defects will impede \( e-h \) plasma transport and cause local variations in the QCSE.

hh1–e1 transition energy. When the beam is positioned far from the fiber, the shift toward higher hh1–e1 energies is reduced due to the reduced carrier density at the fiber center. Figure 9 shows one-dimensional histograms of the hh1–e1 transition energy, the CL DLD contrast, \( \Delta \alpha \), and \( \partial \Delta \alpha / \partial x \). Regions of maximum change in hh1–e1 transition energy are correlated with DLDs in the CL scan (dips in the line scan) and peaks in the \( \partial \Delta \alpha / \partial x \). 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 influence of strain-induced defects on the ambipolar diffusive transport and the simultaneous effect on the QCSE has therefore been imaged with micrometer-scale spatial resolution.

An asymmetry in the spatial distribution of \( \Delta \alpha \) is seen in Figs. 8(a) and 8(b). The regions of largest blue shift are seen along the [110] direction vertically above and below the optical fiber where the image in Fig. 8(a) shows light grey and white. This behavior is indicative of anisotropic transport of the plasma due to the asymmetry that occurs in the formation of misfit dislocations. The anisotropic formation of misfit dislocations is attributed to the chemical inequivalence of 60° misfit dislocations possessing like signs (i.e., having extra half-planes extending in the same direction with respect to the interface plane) and orthogonal (110) line directions. In the shuffle dislocation set, the extra half-plane terminated with a row of group-III and -V atoms is referred to as \( \alpha \) and \( \beta \) type dislocations, and possesses (110) and [110] line directions, respectively. The anisotropy in \( \alpha \) and \( \beta \) type dislocation densities may be due to different levels of stress required to generate \( \alpha \) and \( \beta \) dislocation cores, and the differences in \( \alpha \) and \( \beta \) dislocation propagation velocities. The plasma transport is least impeded by defects when the electron beam
C. Phenomenological approach to a determination of built-in electric field

The energy of the hh1–e1 transition will shift due to the change in built-in field ($F$). The hh1–e1 excitonic transition energy $E_{ex}$ shifts quadratically at low to moderate fields ($\leq 2 \times 10^5 \text{ V/cm}$) and is given by

$$E_{ex} = E_{ex}(0) - aF^2,$$

(15)

where $E_{ex}(0)$ is the hh1–e1 transition energy at zero field and $a$ is a constant which depends on the structure of the MQWs. The parameter $a$ in Eq. (15) can be determined by calculating the difference in $n=1$ electron and hh energies as a function of field. The linear field term due to the Stark ladder will cancel, yielding a hh1–e1 interband transition energy that is quadratic in the field. By performing a fit to the hh1–e1 calculations the quadratic parameter $a$ describing the QCSE is $1.0723 \times 10^{-3} \text{ meV/(kV/cm)}^2$. The other parameter in Eq. (15), $E_{ex}(0)$, is determined by employing a phenomenological approach using the EIBA results as will be described here. For a high-energy electron probe, the size and shape of the electron–hole pair generation region depends on the beam energy. A maximum depth of $\sim 4 \mu m$ is expected for the 30 keV electron-beam energy employed in this study. This beam energy will provide near uniform excitation of the MQW region as the total sample thickness is $\sim 1.2 \mu m$. The excess carrier density is given by

$$\delta n_q = \frac{\tau_{ph} P(1 - f) I_b}{eE_i A_{ex}} \frac{dE_i}{dz},$$

(16)

where $P$ is the nip period, $dE_i/dz$ the electron-beam “depth-dose” or energy dissipation function, $I_b$ the beam current, $f$ the fractional beam loss due to backscattered electrons (for most cases, $f < 1$), $E_i$ the valence electron ionization energy (i.e., the energy required to form an $e−h$ pair), and $A_{ex}$ the effective lateral area of excitation. Due to the generation of excess carriers, the effective nip band gap $V_g$ will increase (by reduction of the built-in space-charge field) and this results in a decrease in recombination time $\tau_{ph}$ according to the phenomenological expression

$$\tau_{ph} = \tau_0 \exp \left[-\frac{e\beta \delta n_q}{2e}\right],$$

(17)

where $\tau_0$ and $\beta$ are parameters which depend on the temperature and the MQW nip structure. Insertion of Eqs. (11) and (16) into Eq. (17) yields

$$F = F_0 - \theta I_b \exp[-\beta(F_0 - F)],$$

(18)

By a nonlinear least-square fitting of the experimental QCSE data, $e1$–hh1 energy versus $I_b$, to Eqs. (18) and (15) with the parameter $a$ obtained from the TMM calculation, a determination of the parameters $\beta$, $E_{ex}(0)$, and $\theta$ was performed. Plots of the $e1$–hh1 excitonic energy and electric-field data (open squares) versus $I_b$ are shown in Fig. 10 for EBIA measurements of a 90 $\mu m \times 90 \mu m$ mesa region. The results of the fit for the mesa region are indicated by the solid lines running through the data. This three parameter fit yields $\beta = 0.10642 \text{ cm/kV}$, $E_{ex}(0) = 1.20477 \text{ eV}$, and $\theta = 8872.1 \text{ kV}$.
FIG. 10. The $\epsilon\hbar$ transition energy for the mesa and planar regions vs $I_b$ in the top portion and the electric field ($F$) for the mesa and planar regions vs $I_b$ in the bottom portion of the figure. The results of the fitting to the phenomenological model are shown by the solid curves. The ambipolar diffusion lengths obtained in the planar region from the phenomenological model vs beam current is shown.

cm nA. Further, from Eq. (15) the calculated values of $F$ are then obtained from the measured $\epsilon\hbar$ excitonic energies and plotted in the lower panel of Fig. 10 (open squares) for the mesa region. The model of Eq. (18) can be applied to the planar region. The parameters $A_{x}$, $B_{x}$, and $C_{x}$ are used to account for the differences in $A_{x}$, $B_{x}$, and $C_{x}$, respectively. Nipi-doped samples possessing similar doping profiles, the diffusion length is typically $\sim$ mm and is excitation dependent.

In the case of the mesa, the electron–hole plasma is confined to the mesa, and thus $A_{x} \approx 8000 \mu m^{2}$. 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. For the planar region, $A_{x} \approx \pi L_D^2$, and $A_{x}$ is excitation dependent. The parameter $\theta$ is therefore excitation dependent in the planar region and can be written as

$$\theta = \kappa (\pi L_D^2)^{-1},$$

where $\kappa$ is excitation independent and $\kappa = 0.7186 \text{ kV cm nA}$, as obtained from $\theta A_{x}$ for the mesa. Substitution of Eq. (19) into Eq. (18) and application of Eq. (15) allows for a determination of both $F$ and $L_D$ vs $I_b$, as indicated in the lower panel of Fig. 10 (with circles and triangles, respectively).

The results illustrate that for a given $I_b \approx 20$ nA, the field in the planar sample is greater than that in the mesa due to a reduction in the electron–hole plasma density. For $I_b \approx 20$ nA, the fields for the mesa and planar regions will coincide due to a reduced ambipolar diffusion length below $\sim 50 \mu m$.

The ambipolar diffusion length is found to approach $\sim 800 \mu m$ for $I_b = 0.1$ nA and decreases to $25 \mu m$ for $I_b = 100$ nA.

A plot of the $\epsilon\hbar$ transition energy versus electric field is shown in Fig. 11. The phenomenological data are shown for the planar and mesa regions (triangles and circles, respectively). Nipi-function-based TMM calculations are shown for various In compositions $x$, as indicated by the different lines. For each experimental $\epsilon\hbar$ energy value, the electric field has been determined using the phenomenological model.

FIG. 11. A plot of the $\epsilon\hbar$ transition energy vs electric field for various In compositions. The experimental points are shown for the planar and mesa regions. Nipi-function-based TMM calculations are shown for various In compositions $x$ as indicated by the different lines. For each experimental point, the electric field has been determined using the phenomenological model.

The values listed above for $E_{ex}(0)$, $\theta$, $\beta$, and $\alpha$ are a result of this iterative procedure. The maximum field $F_0$ obtained with $I_b = 0$ is $\sim 115 \text{ kV/cm}$. This is smaller than the ideal maximum field that should result from the present doping profile which should yield an effective space–charge–induced modulation of the band edges close to the GaAs band gap of 1.424 eV. For the 1000 Å half-period, this should yield a maximum field of $\sim 140 \text{ kV/cm}$ for $I_b = 0$. The reduced value of the built-in field may be related to the defects found in the EBIA imaging. Previously we showed that a large increase in the nipi effective band gap (which is equivalent to a decrease in field) in nipi-doped MQW samples is correlated with a high defect density. Defects can induce the Fermi levels (or
quasi-Fermi levels under excitation) to reside closer to the middle of the gap in the n- and p-type regions, thereby reducing the built-in field.

D. Measurements of excess carrier lifetime and ambipolar diffusion coefficient

The lifetime of excess carriers can be estimated by measuring the 3 dB frequency response, i.e., $\tau_{3\text{ dB}} = 1/(2\pi f_{3\text{ dB}})$. This is accomplished by measuring the normalized transmission modulation $\Delta T/\Delta T_0$ versus frequency for different beam currents, as shown in Fig. 12. We also estimate the lifetime from the phenomenological approach, as described by Eqs. (16) and (17). The value of $\tau_0$ can be determined from the measured $\theta$ parameter found in Eq. (18). From the empirical electron energy-loss model of Everhart and Hoff, we estimate that $dE_p/dz \approx 7.1$ keV/μm, averaged over the entire MQW structure, for a 30 keV electron-beam energy.38 This results in $\tau_0 = (2eE_p)/|PdE_p/dz| = 6.3$ ms. The values of $\tau_{3\text{ dB}}$ and $\tau_{ph}$ [from Eq. (17)] are shown in Fig. 4 as a function of excess carrier density and electric field, next to $\tau_{th}$ which was obtained from the TMM calculations. The values of $\tau_{3\text{ dB}}$ and $\tau_{th}$ are observed to lie close to each other in the range $55\leq F\leq 115$ kV/cm, further confirming the validity of the phenomenological model. Instrumental bandwidth prevented a reliable measurement of $\tau_{3\text{ dB}}$ for lower fields (higher beam currents). The calculated values of $\tau_{th}$ are, however, about nine orders larger than $\tau_{3\text{ dB}}$ and $\tau_{ph}$ for $F=115$ kV/cm. The values of $\tau_{th}$ and $\tau_{ph}$ coincide when $F=0$ where the lifetime ($\sim 10$ ns) is determined by spatially direct radiative recombination. The large discrepancy between $\tau_{th}$ and $\tau_{ph}$ (as well as $\tau_{3\text{ dB}}$) for high fields can be explained by the including the effects of defects, as discussed in Sec. IV B. The theoretical lifetime $\tau_{th}$ described by Eq. (5) does not include the effect of recombination via channels created by defects. These defect states can dominate in the high-field range where the overlap of spatially separated electron and hole wave functions is markedly reduced relative to the overlap of carrier and localized defect-state wave functions. As the field is reduced, the increased overlap of electron and hole wave functions will begin to compete with defect-induced recombination resulting in the convergence of $\tau_{th}$ and $\tau_{ph}$. A determination of the deviation of $\tau_{th}$ and $\tau_{ph}$ at high fields is thus a sensitive indicator of extraneous defect channels and corroborates with the CL and EBIA imaging which reveals the existence of defects that impede diffusive transport.

The ambipolar diffusion coefficient $D_a$ can be determined from the experimental and phenomenological results (denoted as $D_{exp}$) and is

$$D_{exp} = L_{ph}^2 \tau_{ph}^{-1}. \tag{20}$$

A theoretical expression for $D_{a}$ (denoted as $D_{th}$) has been derived by Gulden et al., and is

$$D_{th} = \frac{1}{e^2} \frac{\sigma_n \sigma_p}{\sigma_n + \sigma_p} \frac{\partial \phi_{np}}{\partial n}, \tag{21}$$

where $\sigma_n = n e \mu_n$ and $\sigma_p = p e \mu_p$ are the n- and p-layer conductivities, $n$ and $p$ are the average three-dimensional excess carrier densities which are given by $N_{\text{f}}P$ and $P_{\text{f}}P$, respectively, and $\phi_{np} = \phi_n - \phi_p$ is the difference in quasi-Fermi levels. For the present δ-doped nipi sample, $\partial \phi_{np}/\partial n$ is a constant determined by the change in effective nipi band gap obtained by integrating $(dE/dn)dz$ over half a nipi period [using Eq. (11) and from Poisson’s equation] and results in $\partial \phi_{np}/\partial n = (eP)^2/4\epsilon$. The electron and hole mobilities in GaAs depend strongly on doping concentration as a result of impurity scattering. The mobilities have previously been determined as a function of impurity concentration and for our sample, with an average doping density of $n_i = 6 \times 10^{17}$ cm$^{-3}$, we estimate $\mu_n$ and $\mu_p$ to be 3300 and 180 cm$^2$/V s. Using the GaAs room-temperature mobility results of Ref. 40, we have also included $D_{th}$ curves for impurity concentrations of $6 \times 10^{16}$ and $6 \times 10^{18}$ cm$^{-3}$. The experimental and theoretical ambipolar diffusion coefficients of Eqs. (20) and (21) are shown versus $F$ in Fig. 13. The experimental values for $D_a$ are observed to lie below the theory curves over most of the
electric-field range. It is our hypothesis that the reduced values of $D_a$ are a result of the strain-induced defect atmosphere that reduces the carrier mobility. Previously, using EBIA in a noncontact Shockley–Haynes experiment for a similar nipi In$_x$Ga$_{1-x}$As/GaAs MQW, we showed that there can be a large reduction and anisotropy in $D_a$ caused by strain-induced defects. These defects are expected to reduce the mobility by creating potential fluctuations that increase scattering of mobile carriers. Also, the defects can create a local density of midgap states that will force the Fermi levels (and quasi-Fermi levels under excitation) to reside closer to midgap. This will cause a repulsive barrier that impedes carrier motion. The latter effect also gives rise to repulsion of majority carriers from the edge of a cleaved nipi sample. An elimination of the strain-induced defects will have a marked influence on the EBIA imaging of QCSE, lifetime, and ambipolar diffusion coefficient. Thus the EBIA measurements can serve as a sensitive probe for the presence of defects created by lattice mismatch in nipi-doped In$_x$Ga$_{1-x}$As/GaAs structures.

V. CONCLUSION

In summary, we have investigated the nonlinear optical and transport properties of a nipi-doped In$_x$Ga$_{1-x}$As/GaAs MQW structure using a newly developed experimental approach, EBIA, and theoretical lifetime calculations. Calculations of eigenstates using Airy functions in the transfer-matrix method with a self-consistent field approximation were used to calculate the lifetime as a function of excess carrier density for spatially separated carriers. EBIA was used to study the electron–hole carrier dynamics and influence of defects on plasma transport in nipi-doped MQW structures with a micrometer-scale spatial resolution. A phenomenological approach, using EBIA, was employed to determine the excess carrier lifetime, diffusion coefficient, and built-in electric field as a function of the excitation density. The imaging revealed, with micrometer-scale resolution, the existence of an atmosphere of point defects which impedes ambipolar diffusive transport and reduces the excess carrier lifetime markedly relative to the theoretical calculation of the lifetime. An anisotropy in carrier transport was found in the EBIA imaging consistent with the anisotropy in misfit dislocations, typically found in In$_x$Ga$_{1-x}$As/GaAs structures. These results illustrate the complex interplay between structural, transport, and the nonlinear optical properties of nipi-doped structures utilizing In$_x$Ga$_{1-x}$As/GaAs MQWs. We expect that the EBIA approach illustrated here will serve as a prototype for future studies of spatial variations in electroabsorption in strained materials that are highly susceptible to defect formation.

ACKNOWLEDGMENTS

This work was partially supported by grants from the USC James H. Zumberge Faculty Research and Innovation Fund and the Charles Lee Powell Foundation and was sponsored by the U.S. Army Research Office and the National Science Foundation. We thank Dr. Joe Maserjian of the Jet Propulsion Laboratory for valuable discussions.

FIG. 8. EBIA and CL images of the planar region at \( T = 86 \) K. An EBIA image showing the integrated values of positive \( \Delta \alpha \) in the range \( 955 \leq \lambda \leq 975 \) nm is shown in (a). A new type of EBIA image is displayed in (b) in which the grey scale key represents a wavelength mapping of the spatial distribution of the high-energy \( \Delta \alpha \) peak position. The CL image in (c) shows the DLD network caused by the formation of misfit dislocations.