EFFECTS OF STRAIN-INDUCED DEFECTS ON EXCESS CARRIER LIFETIME
AND AMBIPOLAR DIFFUSION IN nipi-DOPED In0.53Ga0.47As/GaAs MQWs

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ABSTRACT

The effects of strain-induced defects on excess carrier lifetime and transport in a nipi-
doped In0.53Ga0.47As/GaAs multiple quantum well (MQW) structure were examined with a new
method called electron beam-induced absorption modulation (EBIA) in which the kinetics of
carrier transport and recombination are examined with a high-spatial, -spectral and -temporal
resolution. The excess carrier lifetime and ambipolar diffusion were found to be reduced by
factors of \( \sim 10^{13} \) and \( \sim 10^9 \) compared to theoretical values, respectively, and this is attributed to
the presence of strain-induced defects. The MQW excitonic absorption coefficient sensitively
depends on the carrier density in the QWs, as a result of screening of the electron-hole (e-h)
Coulombic interaction. Likewise, ambipolar diffusion is found to depend on the excess carrier
density in a nonlinear fashion, as a result of the e-h plasma-induced changes in the local
depletion widths in the vicinity of structural defects.

INTRODUCTION

Owing to large nonlinear optical effects, the spatially separated electron-hole (e-h) plasma
that can be generated in periodically doped nipi multiple quantum well (MQW) structures,
exhibits potential for applications in electro-optic devices such as spatial light modulators
(SLMs). Because of large enhancements in the excess carrier lifetime and in-plane ambipolar
diffusion constant, an increase of the effective nipi bandgap, MQW excitonic absorption,
and refractive index can be attained by a relatively weak optical excitation.1,3 Also, the large
control over the plasma density in nipi-based SLM structures enables a spatial and
quasi-optical modulation of the transmission and reflection of micro/millimeter waves for
applications in phased-array signal processing, telecommunication, and radiometry, as recently
demonstrated.4,5 The understanding of the behavior of fundamental MQW-nipi parameters, such as
excess carrier lifetime \( \tau \), ambipolar diffusion coefficient \( D_a \) and excitonic absorption
coefficient, \( \alpha \), as a function of excess carrier density is of paramount importance in developing
device applications and enhancing the basic understanding of nonlinear electro-optic effects.

The deleterious influence of defects such as misfit dislocations and the associated Cottrell
atmosphere of point defects on \( \tau \), \( D_a \) and \( \alpha \) need to be examined when working with strained-
layer systems. In particular, the In0.53Ga0.47As/GaAs MQW system, due largely to the transparent
nature of the GaAs substrate with respect to the MQW interband transition energies, is a leading
candidate for photonic device applications. We have previously demonstrated the feasibility of
using a novel technique called electron beam-induced absorption modulation (EBIA)6 to examine
the influence of strain-induced defects on \( \tau \), \( D_a \) and \( \alpha \). In this paper, we have utilized a time-
resolved EBIA technique to study the carrier dynamics associated with nonlinear optical
phenomena in a nipi-doped In0.53Ga0.47As/GaAs MQW structure. Based on a phenomenological
model, \( \alpha \), \( D_a \) and \( \tau \) as a function carrier density and the influence of defects therein are
quantitatively analyzed.

EXPERIMENTAL

The nipi-doped MQW structure was grown by molecular beam epitaxy on a GaAs(001) substrate and consists of 44 In$_{0.15}$Ga$_{0.85}$As QWs, each 65 Å thick, 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. The δ-doping planes induce a linear variation in the band edges along the growth direction as illustrated in Fig. 1. In order to laterally confine the e-h plasma to a well-defined region, conventional lithographic techniques were used to pattern the sample into square mesas of 90 μm × 90 μm. A non-patterned planar region of ~1 cm × 1 cm was examined to study the effects of defects on the ambipolar diffusion of the e-h plasma. In addition to employing EBIA imaging and spectroscopy techniques as previously reported, we have employed a new time-resolved EBIA approach which uses a Boxcar integration technique. The sub-μs time resolution allows for a measurement of absorption modulation decay behavior, enabling a direct determination of the excess carrier lifetime and diffusion parameters. This complements the sub-μm resolution spatial imaging of Δα previously demonstrated with EBIA.

RESULTS AND DISCUSSION

Room temperature EBIA spectra for various electron beam currents, I$_{eb}$, are shown in Fig. 2 for the planar region. The effective QW absorption coefficients, α, were calculated according to (1-α)$_{T}$$\ln T$, where T is the measured normalized transmission through the sample and I$_{eff}$ is the total thickness of the QWs. The peak of the absorption spectrum at ~1005 nm is the n=1 heavy-hole to electron (hh1-e1) excitonic transition. During the continuous generation of e-h pairs by the high-energy (35 keV) electron beam, electrons and holes will be attracted to the QWs and the center of the barriers, respectively, resulting in their spatial separation. Under sufficiently high excitation, the quenching of the hh1-e1 excitonic absorption occurs and is a result of band-filling and screening of the Coulombic interaction of the excitons by the electron plasma filling the QWs. A reliable treatment of screening in semiconductors requires the use of many body theory. For simplicity, however, the screening-induced change in α is often modeled by a simple absorption saturation relationship,

$$\alpha = \frac{\alpha_0}{1 + δn_f/n_{sat}} + \alpha_{p},$$

which is a heuristic fitting equation and not based on a theoretically derived model, where δ$n_f$ and $n_{sat}$, respectively, are the two-dimensional excess

![Fig. 1 Band diagram of nipi-doped MQWs.](image1)

![Fig. 2 Absorption spectra at various $I_e$.](image2)
carrier density and the saturation carrier density, $\alpha_s$ is a band-to-band absorption term, and $\alpha_e$ is the excitonic absorption coefficient in the absence of excitation. The experimental excitonic absorption $\alpha$ as an empirical function of $\delta n_e$ will be determined from the following phenomenological model, and a deviation from the relationship of Eq. (1) will be discussed.

In the EBIA study here, e-h pairs can be generated nearly uniformly throughout the entire $\sim$3.7 $\mu$m MQW region by a 35 keV electron beam. The steady state two dimensional excess carrier density $\delta n_e$ is given by

$$\delta n_e = \frac{\tau P(1-f) I_b dE_b}{eE \tau_{ex} dz},$$

where $\tau$ is the lifetime, $\tau'$ is the nipi period, $dE_b/dz$ is the electron beam "depth-dose" or energy dissipation function, $I_b$ is the beam current, $f$ is the fractional beam loss due to backscattered electrons (for most cases, $f < 1$), $e$ is the electric charge, $E_b$ is the valence electron ionization energy, and $A_{ex}$ is the effective lateral area of excitation. In Eq. (2), $A_{ex}$ for the mesa is $\sim 8100$ $\mu$m$^2$, and the only unknown is $\tau$, which can be described according to the phenomenological expression

$$\tau = \tau_0 \exp \left( -\frac{e\beta \delta n_e}{2e} \right),$$

where $\tau_0$ and $\beta$ are parameters which depend on the temperature and the MQW nipi structure, and $e$ is the dielectric permittivity of GaAs. Insertion of Eq. (3) into Eq. (2) yields,

$$\delta n_e = \frac{2e \theta I_b dE_b}{eE} \exp \left( -\frac{e\beta \delta n_e}{2e} \right),$$

where $\theta = \tau P(dE_b/dz)(1-f)/((2eA_{ex}E_b) \approx 4278.8$ kV/cm-nA. Note that from the empirical electron energy loss model of Everhart and Hoff, we estimate that $dE_b/dz \approx 7.53$ keV/um and $E_b \approx 4.8$ eV for GaAs. Since $\tau$ varies exponentially as a function of $\delta n_e$, the recombination rate, which is proportional to the reciprocal of lifetime $\tau$, is no longer a constant when $\delta n_e$ changes. The time-dependent $\delta n_e$ in the absence of any carrier generation is given by

$$\frac{d}{dt} (\delta n_e) + \frac{\delta n_e}{\tau_0 \exp (-e\beta \delta n_e/(2e))} = 0,$$

and integration yields

$$\delta n_e (t) = \frac{\delta n_e (0)}{1 - \exp (-e\beta \delta n_e/(2e))}$$

$$\Delta \alpha \approx 10^{-3} \text{arb. units}$$

Fig. 3 $\Delta \alpha$ vs. $t_d$ for $I_b=20, 40,$ and 80 pA.

Fig. 4 Experimental and fitted $\alpha$ vs $\delta n_e$ curves.

Mesa

$T = 296 \, \text{K}$

Exp.

Fit

$\alpha \, (10^{-4} \, \text{cm}^{-1})$

$\delta n_e \, (10^{11} \, \text{cm}^{-2})$

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\[
\ln(\delta n_e) + \sum_{n=1}^{\infty} \frac{1}{n} \left[ \frac{-\varepsilon \beta \delta n_e}{(2e)} \right] = -\frac{I}{\tau_o} + \Delta; \quad \Delta = \ln(\delta n_e) + \sum_{n=1}^{\infty} \frac{1}{n} \left[ \frac{-\varepsilon \beta \delta n_e}{(2e)} \right] \tag{6}
\]

where $\delta n_e$ is the initial steady state $\delta n_e$ in the presence of $I_b$ (i.e., before the electron beam is blanked), and can be determined numerically by Eq. (4), provided $\beta$ and $\tau_o$ are determined. In the limit of weak excitation, the differential excitonic absorption $\Delta \alpha$ to a first order of approximation, is proportional to $\delta n_e$, according to Eq. (1). The experimental data of $\Delta \alpha$ vs. $I_b$ (the time delay after a steady-state excitation) at various $I_b$ are shown in Fig. 3. The solid curves are the results of a nonlinear least square fit of this data at $I_b=20, 40,$ and 80 pA simultaneously to Eq. (6), yielding $\beta=0.20074 \text{ cm/kV}$ and $\tau_o=3.08 \text{ msec}$. Note that a further increase of $I_b$ results in a gradual deviation of $\beta$ due to a deviation from the linear relationship between $\delta n_e$ and $\Delta \alpha$, which prevails only at weak excitation ($I_b \leq 100 \text{ pA}$). Inserting the value of $\beta$ and $\tau_o$ into Eq. (4), therefore, allows for a determination of $\delta n_e$, for various $I_b$. The experimental results of $\alpha$ vs. $\delta n_e$ and a fit to the model of Eq. (1) are shown in Fig. 4. The fit gives $n_{\alpha}=2.5 \times 10^{11} \text{ cm}^{-2}$, consistent with previous estimates of $n_{\alpha}$. The quenching of $\alpha$ is found to be more rapid than that described by Eq. (1) when $\delta n_e \geq 1.5 \times 10^{11} \text{ cm}^{-2}$. The observed large deviation between the $\alpha$ vs. $\delta n_e$ curve and the fit of Eq. (1) in Fig. 4 is attributed to an absence of a treatment of screening in the model of Eq. (1) which, as we show, should only be used as a rough approximation.

Using Eq. (3), the data of Fig. 4, and the aforementioned values of $\beta$ and $\tau_o$, the relationships of $\delta n_e$ and $\tau$ as a function of $I_b$ in the planar region can be determined and are shown in Fig. 5. We have previously shown that, in another nip-nip-doped MQW structure under a weak excitation, a nearly 9 orders of magnitude reduction of $\tau$, as compared to a theoretically calculated lifetime, $\tau_{\text{th}}$, is attributed to the presence of defects which provide additional recombination channels. Similarly, $\tau_o$ here is $10^{13}$ less than the $\tau_{\text{th}}$ calculated by Jonsson et al. for an effective nip-nip barrier height of 1.257 eV for this nominal structure. Such a reduction in lifetime confirms the effect of structural defects on increasing the recombination rate of excess carriers.

The model of Eq. (4) can be applied to the planar region, provided a few modifications are made to account for the variation in $A_{\alpha}$. In contrast to the confined mesa region, $A_{\alpha}$ is equal to $\pi L_{\alpha}^2$ and the diffusion length $L_{\alpha}$ is excitation dependent for the planar region. The parameter $\theta$ is thus excitation dependent in the planar region and can be written as

\[
\theta = \kappa (\pi L_{\alpha}^2)^{-1} \tag{7}
\]

where $\kappa$ is excitation independent and $\kappa=0.3466$ kV cm/nA, as obtained from $\theta A_{\alpha}$ for the mesa. Substitution of Eq. (7) into Eq. (4) with the results of $\delta n_e$ vs. $I_b$ shown in Fig. 5(b) allows for...
the determination of $L_p$ and $D_a$ ($=L_p^2/\tau$) as a function of $\delta n_a$ as shown in Figs. 6(a) and 6(b), respectively. A theoretical expression for $D_a$ (designated as $D_{th}$) has been derived by Gulden et al.\textsuperscript{15} and is

$$D_{th} = \frac{1}{e^2} \frac{\sigma_n \sigma_p}{\sigma_n \sigma_p} \frac{\partial \phi_{mp}}{\partial n},$$

where $\sigma_n = n \mu_n$ and $\sigma_p = p \mu_p$ are the $n$- and $p$-layer conductivities, $n$ and $p$ are the average 3-dimensional excess carrier densities which are given by $\delta n_r / P$ and $\delta n_l / P$, respectively, and $\phi_{mp} = \phi_n - \phi_p$ is the difference in quasi-Fermi levels. The 2D excess hole density, $\delta n_p$, is given by $\delta n_p = \delta n_l + \delta n_r$, since most of the dopants are ionized at room temperature. An excess $\delta p$ doping concentration of $\delta N_p = 3 \times 10^{12} \text{ cm}^{-2}$, relative to $\delta n$ doping, was inserted in order to locate the Fermi-level sufficiently far below the electron ground state in the QWs to ensure that the QWs are essentially free from electrons under thermal equilibrium. The lower limit for the ideal mobilities $\mu_n$ and $\mu_p$ are estimated to be ~3100 and ~170 cm$^2$/V-s, respectively, for equivalent 3-dimensional doping densities in GaAs.\textsuperscript{16} For the present $\delta$-doped nip$i$ structure, $\partial \phi_{mp} / \partial n$ is approximately a constant\textsuperscript{19} and is given by $\partial \phi_{mp} / \partial n = (eP)^2/\hbar e$. The theoretical diffusion coefficient, $D_{th}$, versus $\delta n_p$ is plotted in Fig. 6(b). The experimental values for $D_a$ are observed to lie nearly 3 orders of magnitude below $D_{th}$ for $\delta n_p \leq 0.5 \times 10^{11} \text{ cm}^{-2}$, and gradually increase to within ~20% of $D_{th}$ for $\delta n_p \gtrsim 3.0 \times 10^{11} \text{ cm}^{-2}$. In a previous study,\textsuperscript{2,13} it was shown that the reduction of $D_a$ was caused by strain-induced defects which create potential fluctuations that increase scattering of mobile carriers. The reduction in discrepancy between $D_a$ and $D_{th}$ for higher carrier concentration was not observed in the study of Ref. 12 since only very low carrier concentrations were examined. It is our hypothesis that the convergence of $D_a$ and $D_{th}$ for higher concentrations is related to changes in the local depletion width surrounding point defects and misfit dislocations in the MQW. These 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 mid-gap, inducing a repulsive barrier that impedes carrier motion. The latter effect also gives rise to the repulsion of majority carriers from the edge of a cleaved nip$i$ sample. Each defect will cause a 3-D depletion region whose complex shape will depend on the local doping density and carrier concentration. The increase in local carrier concentration caused by the excitation will reduce the size of the depletion region and reduce the magnitude of the potential fluctuations by screening the charge associated with the defects. The effective reduction in scattering cross-section at higher excess carrier concentrations will consequently result in an increased $D_a$, as experimentally observed.

**CONCLUSION**

In conclusion, the modulation of MQW exciton absorption has been studied with the use of a novel time-resolved EBIA technique. The excess carrier lifetime and ambipolar diffusion coefficient are found to be reduced by factors of ~10$^{15}$ and ~10$^{3}$, respectively, relative to
theoretical values for the low excitation densities. This reduction is attributed to the strain-induced misfit dislocations and point defects. A more rapid decrease of $\alpha$ for high carrier densities than that predicted by the conventional absorption saturation relationship suggests that a more sophisticated model which incorporates the effect of screening needs to be developed. The experimentally determined ambipolar diffusion coefficient, $D_a$, is found to approach its theoretical estimate, $D_{th}$, as the carrier density is increased. This phenomenon is suggested to be caused by a reduction in (i) the size of defect-induced depletion regions and (ii) the height of band-edge potential fluctuations for increased carrier densities.

ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Army Research Office and the National Science Foundation.

REFERENCES