Enhanced ambipolar in-plane transport in an InAs/GaAs hetero-n-i-p-i

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In-plane transport in an InAs/GaAs semiconductor hetero-n-i-p-i has been investigated using picosecond transient grating techniques and an order-of-magnitude enhancement of the ambipolar transport relative to that measured in a similar undoped sample has been demonstrated. Both the magnitude and the density dependence of this enhanced transport are consistent with an additional driving force that is associated with an in-plane modulation of the screened n-i-p-i field. This modulation is the result of the spatial separation by perpendicular transport of electrons and holes that also have an in-plane density modulation.

I. INTRODUCTION

Quantum-well hetero-n-i-p-i's are among several semiconductor structures that continue to attract interest for possible applications to low-power two-dimensional switching arrays and all-optical spatial light modulators by exploitation of quadratic (rather than linear) electro-optic effects. The turn-on time for such a n-i-p-i device is usually determined by carrier transport perpendicular to the quantum wells. More specifically, it is determined by the time required for carriers generated in the quantum wells to escape the wells and to move to screen the built-in electric field, thus blue shifting the exciton by reducing the quantum-confined Stark effect (QCSE). Typical turn-on times determined by these processes have been measured to be of the order of a few ps. By contrast, the recovery (or turn-off) time for a hetero-n-i-p-i, when it is used in the conventional single-beam geometry, is determined by the slow recombination of the spatially separated charges in the doped regions and is typically in the range of μs-μms. Recently, instead of using a single beam, considerable attention has been given to two-beam mixing geometries, where quadratic photodiffractive gratings are written in the quantum-well structures by the interference of the two beams. If such a geometry is used with the hetero-n-i-p-i, switching arrays and all-optical spatial light modulators by quantum-continual Stark effect (QCSE). In both cases, the geometries take advantage of large nearly resonant transport-related nonlinearities in thin structures to operate in the Raman–Nath regime.

Here, we present measurements of the decay of photodiffusive gratings written in a hetero-n-i-p-i by the interference of two pulses tuned near or on the n=1 electron to n=1 heavy hole (E1H1) excitonic transition. As we later discuss, such excitation can produce absorptive and refractive gratings that are associated with a modulation of the excitonic bleaching or absorptive and refractive gratings associated with a modulation of the QCSE, depending on the time scale and writing fluence. In the regime where a modulation of the QCSE dominates, we show that the perpendicular separation of the photogenerated charge, caused by the built-in field, actually speeds the decay by roughly an order of magnitude by enhancing the effective in-plane ambipolar transport (in contrast to the single beam geometry where charge separation elongates the recombination and recovery time). We compare these dynamics to the measured decay of gratings written in a similar flatband undoped sample. Finally, we describe a simple phenomenological model that provides qualitative and quantitative agreement with the magnitude and density dependence of the measured effective diffusion coefficient.

Enhanced transport also has been reported recently in two other heterostructures where charge separation is dictated by applied or built-in fields. In the first of these, high-speed diffusive conduction was measured in a highly doped transmission-line-like GaAs/AlGaAs p-i-n structure by using a pump-probe technique that employed spatially separated and tightly focused pulses. In the second, a gi-
The p-type InAs/GaAs semiconducting hetero-n-i-p-i used in these studies was grown on a GaAs substrate oriented in the (100) direction. The n and p region of the hetero n-i-p-i are each 20-nm-thick layers of GaAs and are doped to $2 + 1 \times 10^{17}$ and $1.2 + 0.6 \times 10^{18}$ cm$^{-3}$, respectively, as determined by secondary ion mass spectroscopy (SIMS). Each intrinsic region is 120 nm wide, at the center of which are three 11-nm-wide quantum wells separated by 14-nm-thick barriers. The sample contains 12 periods of the n-i-p-i structure, making a total of 72 quantum wells. Each well consists of six periods of an all-binary InAs/GaAs short-period strained-layer superlattice. Specifically, each quantum well is composed of six layers of InAs, each two monolayers thick, alternating with five layers of GaAs, each five monolayers thick. It should be noted that the all-binary and strained nature of these quantum wells are not directly related to the fast in-plane transport to be described in this article. The electric field in each intrinsic region was calculated to be 27 kV/cm for the best estimate of the dopant densities. The growth of the all-binary quantum wells$^{9,10}$ and the measurement of the non-linearities and charge transport associated with single-beam excitation of this structure are described in detail elsewhere.$^1$ For the purposes of comparison, measurements were also performed on an undoped, flatband multiple-quantum-well sample that contains 50 equally spaced quantum wells separated by 20 nm GaAs barriers. Each well was identical to that described above.

A conventional transient grating technique was used to measure the in-plane ambipolar transport at room temperature. The pulses used in our experiments had a duration of approximately 1 ps and were produced by a cavity-dumped, synchronously mode-locked dye laser that was tuned to the center of the F1H1 excitonic transition at 967 nm. Each pulse from the laser was split into three parts. Two of the pulses, one a factor of 20 weaker than the other, were spatially and temporally overlapped in the sample with an angle of $11^\circ$ between the two beams. The absorption of these two interfering pulses produced a $\pm 43\%$ modulation of the carrier density in the quantum wells with a period of 5 $\mu$m. The grating decay was monitored by measuring the diffraction efficiency of the third, probe, pulse as a function of time delay with respect to the pump pulses. To ensure that the mean carrier density remained relatively constant over the probed region, the diameter of the focused probe pulse was chosen to be one-third the diameter of the pump pulses at the sample. These measurements were performed as a function of carrier density (i.e., fluence) while maintaining a constant modulation. Similar measurements were also performed in the undoped multiple-quantum-well sample.

Other important features of these studies are that we chose the sample and arranged the experimental geometry (e.g., grating spacing) to ensure that the grating decay would be slow compared to the grating formation, that the decay would be fast compared to any recombination, and that the sample would recover fully by recombination between successive pump excitations. We have shown previously$^1$ that the nonlinear absorption changes in this hetero-n-i-p-i structure under our excitation conditions are determined by phase space filling and by a blueshift of the exciton associated with screening of the QCSE and that the relative contribution of each is a complicated function of time, wavelength, and fluence. Nevertheless, the turn-on time for the diffraction efficiency is never more than a few ps, since the excitonic bleaching is instantaneous and since the turn-on time for the screening is $\sim 5$ ps. As we demonstrate here, once formed, these photogenerated absorptive and refractive gratings will decay by in-plane transport on much longer time scales. Eventually, the carriers will recombine nonexponentially on time scales that range from $\sim 10$ ns to $\sim 1$ $\mu$s, depending on density. To allow the recombination to be more than 90% complete before the next pump excitation and to avoid thermal effects, the cavity dumper was operated at a frequency of 1 MHz.

III. RESULTS

In Fig. 1, the decays of the gratings written in the hetero-n-i-p-i for several values of the pump fluence (i.e., carrier densities) are compared to the decay in the undoped multiple-quantum-well sample. The decay rate of the grating in the undoped multiple-quantum-well sample is independent of fluence over the range shown. By contrast, the decay rates for the gratings written in the hetero-n-i-p-i sample are a strong function of fluence and are sig-

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**FIG. 1.** Diffraction efficiency, $\eta$ vs probe delay at a grating spacing of $5 \mu$m for the hetero-n-i-p-i for mean fluences 0.6, 2.2, and 17 $\mu$J/cm$^2$, which correspond to carrier densities $2.3 \times 10^{16}$, $8.4 \times 10^{16}$, and $6.5 \times 10^{17}$ cm$^{-3}$, and for the undoped multiple-quantum-well sample for a mean fluence of 2.0 $\mu$J/cm$^2$, which corresponds to a mean carrier density of $1.2 \times 10^{17}$ cm$^{-3}$. 

**Note:** The values are approximate and must be modified.
Fig. 2. Effective ambipolar diffusion coefficient $D_a$ as a function of average injected carrier density for the hetero-n-i-p-i (squares) and for the undoped multiple-quantum-well sample (diamonds). Calculated $D_a$ for a hetero-n-i-p-i with dopant densities $N_p=3.0 \times 10^{17}$ cm$^{-3}$ and $N_n=5.0 \times 10^{17}$ cm$^{-3}$ (solid line), for a sample uniformly doped to the same level (dotted line), and for an undoped sample (dot-dashed line).

Significantly larger than the grating decay rate of the undoped multiple-quantum-well sample. In each case, the decay of the diffraction efficiency is exponential, and the decay time is short compared to the recombination, which was independently determined from pump-probe transmission measurements. Under such condition, if one assumes that the decays are diffusive, the grating lifetime can be expressed as

$$\tau_G = \frac{\Lambda^2}{4\pi^2 D_A}, \tag{1}$$

where $\Lambda$ is the grating spacing and $D_A$ is an effective ambipolar diffusion coefficient, which is discussed below.

The effective ambipolar diffusion coefficients extracted in this way are plotted in Fig. 2 as a function of average carrier density for the hetero-n-i-p-i and for the undoped sample. A density-independent value of 18.5 cm$^2$/s is measured for the undoped sample, a value that is comparable to that expected for GaAs.$^{11}$ By contrast, a strongly density-dependent effective diffusion coefficient is obtained for the hetero-n-i-p-i sample. Notice that the peak value of 180 cm$^2$/s is ten times that measured in the undoped sample and that the coefficients extracted for the hetero-n-i-p-i tend toward that of the undoped sample at the highest carrier densities. The solid, dashed, and dot-dashed curves are the results of calculations to be discussed later.

IV. PHENOMENOLOGICAL MODEL

Previously we have shown$^1$ that photoexcitation of our hetero-n-i-p-i with ps pulses tuned to the E1H1 excitonic resonance, as shown schematically in Fig. 3(a), will lead to an initial bleaching of this transition as the result of phase space filling. The excitons thus created will ionize on a sub-ps time scale to create a confined population of thermalized electrons and holes. Small fractions of the electrons and holes in the tails of the thermalized distributions will have sufficient energy to readily escape the wells and, under the influence of the built-in electric field, will be swept towards the $n$- and $p$-doped GaAs regions, thus, reducing the field and flattening the bands, as illustrated in Fig. 3(b). As carriers escape, the distributions continuously rethermalize, allowing more carriers to escape. This

![FIG. 3. Schematic of the optical response of the hetero-n-i-p-i; (a) photoproduction of carriers by optical excitation on the E1H1 excitonic resonance, (b) followed by a flattening of the bands as electrons and holes escape from the wells and are swept towards the doped regions.](image)

![FIG. 4. Potential energy (a) and the superposed electron and hole distributions (b) in the hetero-n-i-p-i following carrier generation into the wells, but before significant carrier escape and drift, and well before any in-plane transport.](image)
FIG. 5. Potential energy (a) and the electron and hole distribution (b) in the hetero-n-i-p-i following carrier escape from the wells and the perpendicular drift of the carriers to screen the field, but before significant in-plane transport.

The enhanced decay of the photogenerated refractive and absorptive gratings written in the same sample can be understood qualitatively by phenomenologically incorporating the in-plane carrier modulation and transport into the description that was presented in the preceding paragraph and in Ref. 10, as illustrated pictorially in Figs. 4–6. The initial modulations of the conduction (and valence) band potential energy surface and of the electron (and hole) distribution, following excitation with two δ-function (in-time) pump pulses, are depicted in Figs. 4(a) and 4(b), respectively. Since the doped regions (20 nm) in our hetero-n-i-p-i are narrow compared to the intrinsic regions (120 nm), for our purposes here, we take the modulation of the potential energy to be triangular in form, as would be appropriate for a δ-doped structure. Also, for ease of presentation, we ignore the potential associated with the three narrow wells located in the intrinsic region, although we explicitly take them into account in sketching the initial electron (hole) distribution, as shown in Fig. 4(b). Notice that Fig. 4 is not drawn to scale. Specifically, notice that the separation between peaks and troughs in the potential (i.e., n- and p-doped regions) is 140 nm and that the period of the in-plane carrier modulation is 5 μm. For times short compared to the thermal escape time (~5 ps), the carriers will be confined to the wells, there will be no separation of charge, and thus, there will be no screening of the QCSE associated with the built-in field. For this period, the refractive and absorptive gratings will be associated with a bleaching of the exciton.

Because of the relatively large in-plane grating period, the electrons (holes) escape the wells and move to the troughs (peaks) of the potential before any significant in-plane transport can occur. This drift produces electron and hole distributions that are spatially separated in the perpendicular direction and periodically modulated in the plane of the sample, as shown in Fig. 5(b). This separated charge, in turn, screens the built-in field and causes a blueshift of the excitonic resonance by reducing the QCSE. The screening and the blueshift will be largest where the separated carrier densities are largest, that is, near the peak of the carrier modulation. Consequently, the thermal escape and perpendicular drift of the electrons and holes under the influence of the built-in field produces a potential that is periodically modulated in the plane of the sample, as well as in the growth direction, and that resembles that...
shown in Fig. 5(a). In addition, the initial absorptive and refractive gratings that were associated with excitonic bleaching have decayed and been replaced by gratings associated with a blueshift of the exciton.

The potential energy surface and carrier distributions shown in Fig. 5(a) and Fig. 5(b), respectively, represent the initial conditions for the in-plane decay of the carrier grating following perpendicular transport for average carrier densities that are less than those required to produce complete screening. We emphasize that there are two driving terms for the in-plane transport evident in Fig. 5. The first of these is the usual in-plane density gradient, $\nabla \rho (\nabla \rho)$, for the electrons (holes). The second, additional, source is the periodic in-plane gradient of the potential, $\nabla \Phi_{\text{np}}$. Here the in-plane gradient $\nabla \rho = (\partial \rho / \partial x, \partial \rho / \partial y)$. Under conditions described here, the magnitude of $\nabla \Phi_{\text{np}}$ is proportional to the gradient in the electron (or hole) density, $\nabla \rho$ (or $\nabla \rho$), since the degree of screening is proportional to the spatially separated electron and hole densities. Moreover, because the electrons and holes are spatially separated in the growth direction, the sign of the in-plane gradient and, therefore, of the in-plane field seen by the electrons will be opposite to that seen by the holes. Consequently, the field associated with $\nabla \Phi_{\text{np}}$ will force the electrons and holes to move in the same direction in the plane of the sample. While strictly speaking this is a drift term, it is unusual in that it appears diffusive in nature. That is, its magnitude is proportional to the in-plane gradient in carrier density, and it encourages both the electrons and holes to move from regions of high concentrations to regions of lower concentration. In this way, the force arising from the in-plane potential gradient reinforces that from the density gradient to speed the decay of the grating.

Under the influence of these forces, but before significant recombination can occur, the in-plane modulation of both the potential energy and the carrier density will decay, as shown in Fig. 6. At this point, the potential now resembles a uniformly screened version of the initial potential, and the electron and hole distributions are uniform in the plane of the sample, but remain spatially separated in the perpendicular direction. Eventually, the spatially separated electrons and holes will recombine very nonexponentially, as described in Ref. 1. Clearly, the enhancement described here will not occur in our undoped sample, since it requires charge separation and screening.

For pump fluences sufficiently large to produce average carrier densities larger than those necessary to completely screen the built-in field and to approximately flatten the bands, the in-plane decay dynamics differ from those shown in Figs. 4-6. At these large fluences, carriers will escape the wells only until the field is uniformly screened and the bands become approximately flat. The excess carriers (i.e., those not needed to screen the field) will remain in the wells and will continue to produce a bleaching of the exciton. In this case, since there is no in-plane modulation of the potential, the carriers in the wells will decay as in an undoped sample, driven only by the density gradient. In this way, ambipolar transport in the hetero-n-i-p-i approachs that in an undoped sample at high fluences and carrier densities, in agreement with our measurements.

V. ANALYSIS

Rigorous modeling of the processes described in the previous section would require the self-consistent solution of the coupled equations for the electron and hole currents,

$$j_e(r) = e \mu_e \nabla E + e D_n \nabla n,$$  \hspace{1cm} (2)

$$j_p(r) = -e \mu_p \nabla E - e D_p \nabla p,$$  \hspace{1cm} (3)

together with Poisson's equation,

$$\nabla \cdot E = (e/e) (p - n - N_A + N_D),$$  \hspace{1cm} (4)

while allowing for the generation of carriers, neglecting recombination, and requiring continuity,

$$\frac{\partial n}{\partial t} = e^{-1} \nabla \cdot j_e + \frac{\alpha I}{h \nu},$$  \hspace{1cm} (5)

$$\frac{\partial p}{\partial t} = -e^{-1} \nabla \cdot j_p + \frac{\alpha I}{h \nu},$$  \hspace{1cm} (6)

where in these equations $n(p)$, $j_e(j_p)$, $\mu_e(\mu_p)$, and $D_n(D_p)$ denote the electron (hole) densities, currents, mobilities, and diffusion coefficients, respectively, and where $N_A$ and $N_D$ are the acceptor and donor dopant densities in the $p$- and $n$-doped regions, respectively. In addition, $e$ labels the elementary charge, $\epsilon$ the permittivity, $h \nu$ the photon energy, and $\alpha$ the density-dependent absorption coefficient. The self-consistent field $E$ will include the built-in $n-i-p-i$ field and the space-charge field produced by the perpendicular and in-plane separation of electrons and holes, which screens the built-in field and forces ambipolar transport. The self-consistent potential will be given by $E = -\nabla \Phi$.

Since the carrier motion in the growth direction and in the plane of the sample are in general coupled, the exact solution of these coupled equations requires the use of tedious numerical techniques; however, if we incorporate the reasonable approximations used in the phenomenological picture given in the previous section, we can obtain a closed form solution for the effective in-plane diffusion coefficient. Specifically, since the width of the doped regions is substantially narrower than that of the intrinsic regions, we approximate our structure with a $\delta$-doped $n-i-p-i$ structure containing an equivalent sheet charge density. This allows us to take the built-in potential to be triangular in shape, as illustrated in Fig. 4(a). Moreover, as before, we assume that carrier generation and transport in the perpendicular growth direction $z$ are fast compared to transport in the plane of the sample (taken to be the $x$ direction). That is, since the $n-i-p-i$ period (140 nm) is small compared to the optical grating period (5 $\mu$m), we assume that drift and diffusion in the perpendicular ($z$) direction have come to equilibrium and that the electrons and holes cluster about the doped regions to screen the field, as illustrated in Fig. 5. This is our principal approximation, since it allows us to take the $n-i-p-i$ potential energy $e \Phi_{\text{np}}$ to be triangular in form in the transverse $z$ direction (for a fixed in-plane coordinate $x$) even when screened. The latter is
reasonable except at fluences where the carrier screening reduces $\Phi_{n-i-p-i}$ to $\sim kT$, where $k$ is the Boltzmann constant and $T$ is the lattice temperature. As the sample approaches these "flatband" conditions, the carriers will no longer remain clustered in regions near the doped layers and the potential surfaces will no longer appear triangular. Phenomenologically, we handle this limited range by adding the requirement that the potential energy approaches flatband conditions exponentially with increasing carrier density.

Explicitly, for fully compensated or p-type semiconducting samples, we take the modulation of the triangular potential to be of the form

$$e\Phi_{n-i-p-i}(x,z) = -\left(\frac{4kTz}{N_L}\right)\left[\bar{N}_D - n_c \left[1 - \exp\left(-\frac{\bar{n}}{n_c}\right)\right] \right]$$

for $-\frac{1}{4} < z < \frac{1}{4}$,

$$= + \left(\frac{4kT(z - l/2)}{N_L}\right)\left[\bar{N}_D - n_c \left[1 - \exp\left(-\frac{\bar{n}}{n_c}\right)\right] \right]$$

for $\frac{1}{4} < z < \frac{3l}{4}$,

(7)

where $l$ is the $n-i-p-i$ period; the bar "\~" denotes an average of a quantity over the period $l$ and $N_c$ and $n_c$ are critical densities defined as

$$N_c = \left(\frac{8e^2kT}{e^2}\right)$$

and

$$n_c = \bar{N}_D - \bar{n}.$$  

(8)

(9)

Notice that the peak modulation of potential energy of the $n-i-p-i$ is linear in photogenerated density for average electron densities $\bar{n} < n_c$.

$$e\Phi_{n-i-p-i}(\text{peak}) = (kT/N_c)\left(\bar{N}_D - \bar{n}\right).$$

(10)

In this limit, the physical significances of the critical densities $N_c$ and $n_c$ become clear. The critical density $N_c$ corresponds to that change in average carrier density $\bar{n}$ that will produce sufficient screening to lower the peak built-in potential energy by $kT$, and $n_c$ is the average density necessary to drive the bands to within $kT$ of their flatband condition. Moreover, it is clear that this potential energy given by Eq. (7) is the source of an additional drift force that is proportional to the in-plane gradient of the density and that will aid diffusion,

$$eE_{n-i-p-i} = -\frac{\partial(e\Phi_{n-i-p-i})}{\partial x}$$

$$= -\left(\frac{4kTz}{N_L}\right)\exp\left(-\frac{\bar{n}}{n_c}\right)\frac{\partial \bar{n}}{\partial x}, \text{ for } -\frac{1}{4} < z < \frac{1}{4},$$

$$= \left(\frac{4kT(z - l/2)}{N_L}\right)\exp\left(-\frac{\bar{n}}{n_c}\right)\frac{\partial \bar{n}}{\partial x}, \text{ for } \frac{1}{4} < z < \frac{3l}{4}.$$  

(11)

VI. SUMMARY AND CONCLUSIONS

We have used transient grating techniques to measure a factor of 10 enhancement of the effective in-plane ambipolar diffusion coefficient of a p-type semiconducting InAs/GaAs hetero-n-i-p-i over that observed in a similar undoped structure containing identical quantum wells. This enhancement has been shown to be associated with the separation of positive and negative charge in the growth direction caused by the built-in $n-i-p-i$ field. This latter point was demonstrated not only by comparison to the equivalent undoped sample, but by demonstrating that the diffusion coefficient approached the bulk value at carrier densities sufficient to completely screen the field and to drive the hetero-n-i-p-i near flatband conditions. We attribute this enhancement of the in-plane transport to an additional drift term associated with a gradient in the $n-i-p-i$ potential caused by an in-plane modulation of the screening of the built-in electric field.
Good qualitative and reasonable quantitative agreement to the measured density-dependence of the enhanced in-plane transport coefficients has been obtained by using a simple phenomenological model that allows a closed form solution. In this calculation, we have assumed that carrier generation and perpendicular transport are complete before in-plane transport begins, and we have approximated the hetero-n-i-p-i by a delta-doped n-i-p-i structure. All of these assumptions are reasonable for the structure, the pulse widths, and the grating spacings used in the experiments described here. We emphasize that the expressions obtained here are directly applicable only for completely compensated or p-type semiconducting structures that can be reasonably viewed as delta-doped, although they can readily be modified for n-type samples by carefully reversing the roles of electrons and holes and of acceptors and donors. Under the assumption that carrier generation and perpendicular transport are complete, the calculation of enhanced in-plane transport coefficients for semimetals and for uniformly doped structures are also straightforward, but the expressions are slightly different in form from those given here.

Most importantly, we emphasize the limitations of the phenomenological model presented here. If structures with larger enhancements are designed or smaller grating spacings are used in the experiments, the characteristic time for in-plane transport will approach that for the perpendicular transport. Under these circumstances, in-plane and perpendicular transport can no longer be decoupled as we have done here. That is, in-plane transport will occur simultaneously to, and will influence the details of, the perpendicular transport and vice versa. In this case, a complete description of the charge transport may require numerical techniques. Finally, it should be noted that the model presented here does not provide detailed information about perpendicular carrier location near flatband conditions. For average carrier densities significantly larger than 10^{16} \text{ cm}^{-3} (averaged over the n-i-p-i period, not an in-well density), the built-in n-i-p-i field is essentially completely screened, and the carriers tend to remain in the wells rather than in the doped regions. In this case, the grating is associated with excitonic bleaching, and it decays primarily by in-plane transport of the carriers that remain within the wells. Nevertheless, since the ambipolar diffusion coefficient associated with the wells under flatband condition is approximately equal to that of the intrinsic or doped bulk GaAs regions, this detail is unimportant to calculating the in-plane transport in this regime and does not produce a significant deviation from our simplified model.

From a practical standpoint, the enhanced in-plane transport observed here will speed the decay of gratings in (and thereby reduce the turn-off time of) hetero-n-i-p-i devices based on two-beam mixing geometries. On the other hand, the very mechanism that leads to the enhanced transport, namely, the separation of the photoinjected carriers, also greatly increases the carrier recombination time. Therefore, although the grating can be made to decay as fast as \sim 2 \text{ ps} (by using a 1 \mu m grating spacing), roughly 1 \mu s is required for recombination in the hetero-n-i-p-i sample studied here to be 90% complete. Consequently, in practical applications requiring either steady-state or a high repetition rate operation, significant carrier accumulation would be expected. However, as we have demonstrated, as carriers accumulate, the enhanced in-plane transport slows, and the carrier recombination rate accelerates. This strong dependence of both in-plane ambipolar transport and recombination rates on carrier density, which is associated with perpendicular transport, charge separation, and screening in hetero-n-i-p-i's and which we have demonstrated here, will have a profound influence on either the steady-state or pulsed operation of such devices and must be taken into account when modeling or designing these devices.

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