

# High-speed absorption recovery in quantum well diodes by diffusive electrical conduction

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We present here picosecond time-resolved electroabsorption measurements in GaAs quantum well *p-i-n* diode structures. While the dynamics of the vertical transport is not completely understood at present, our data reveal the importance of the "lateral" propagation of the photoexcited voltage pulse over the area of the doped regions. We propose a two-dimensional "diffusive conduction" mechanism, which predicts a fast relaxation of the electrical pulse, with time constants ranging from 50 fs to 500 ps, determined by the size of the exciting spot, the resistivity of the doped regions, and the capacitance of the intrinsic region.

The number and degree of sophistication of quantum well (QW) optoelectronic devices has rapidly increased during the past few years.<sup>1-3</sup> Most of these devices rely on the quantum-confined Stark effect (QCSE), and use QWs in the intrinsic region of a *p-i-n* structure. As these absorptive devices are scaled to higher powers and speeds, it becomes increasingly important to understand the dynamics associated with the photoexcited charge.

In this letter we report results of a study of the dynamics of the photocarriers and the voltage (and consequently absorption) changes they induce in reverse-biased QW *p-i-n* structures. We concentrate here on the mechanism by which the changes in absorption recover after excitation with a small light spot. We excite the carriers using a 6–10 ps laser pulse focused to a small spot [see Fig. 1(c)]. The resulting photocurrent transiently reduces the voltage across the diode, locally in the region of the spot, because the photogenerated carriers move to the electrodes to screen the field. These voltage changes in turn give rise to absorption changes through the QCSE electroabsorption. We monitor these changes with a second time delayed and spatially displaced pulse [see Fig. 1(c)], and we follow their equilibration over the whole diode. We find that this equilibration behaves like a very fast diffusion, and we explain it not as a lateral diffusion of the photoexcited carriers, but as an electromagnetic propagation in a dissipative structure. This therefore gives a new, fast absorption recovery mechanism in such structures, modeled as follows.

In Fig. 1(a) we show schematically a typical dissipative, one-dimensional transmission line. It is well known in such lines that the propagation of a voltage pulse is "diffusive," i.e., it obeys a differential equation with an effective diffusion coefficient of  $1/R_L C_L$  where  $R_L$  and  $C_L$  are the resistance and capacitance per unit length, respectively. In the case of our *p-i-n* diode [Fig. 1(c)], we have conducting surfaces (the *p* and *n* regions) with resistances per square ( $R_{sq}$ ), between which we have capacitance per unit area  $C_A$ . Analogously to the line, we can derive the equation for the evolution of the voltage,  $V$ , in time and two-dimensional ( $x$ - $y$ )

space by considering the model structure as sketched in Fig. 1(b) to obtain

$$\frac{dV}{dt} = D \nabla_{xy}^2 V, \quad (1)$$

where  $\nabla_{xy}^2$  is the two-dimensional Laplacian operator, and the effective diffusion coefficient  $D$  is given by  $D = 1/R_{sq} C_A$ ; here  $R_{sq}$  is the sum of the resistances per square of the *p* and *n* layers. If we were suddenly to place equal and opposite Gaussian distributions of charge of the form  $(2Q_{tot}/\pi w_0^2) \exp(-2r^2/w_0^2)$  on the *p* and *n* layers, respectively,  $V(r, t)$  would be the solution of Eq. (1):

$$V(r, t) = V_M \frac{\tau_c}{t + \tau_c} \exp\left(-\frac{r^2}{4D(t + \tau_c)}\right). \quad (2)$$

Here  $\tau_c = w_0^2/8D$ ,  $V_M = 2Q_{tot}/\pi w_0^2 C_A$ , and the normalization of the charge distribution is such that  $Q_{tot}$  is the total added charge on either plate. Thus the voltage appears to "diffuse" out over the structure. The characteristic time  $\tau_c$  is the time after which the area of the voltage distribution doubles.

Note that the diffusive behavior does not represent actual diffusion of the added electrons and holes, and consequently is not limited by the maximum velocities at which such particles can move. The resolution of this paradox is the same as that in a coaxial line, in which a signal voltage can propagate at the speed of light even though the electrons cannot propagate that fast in metal; the requisite current to move the small perturbation in the charge density rapidly is provided by the low velocity movement of the large charge density in the conductor.

The samples were grown by molecular beam epitaxy on GaAs substrates, with the QW layers sandwiched between AlGaAs *n*- and *p*-doped layers, transparent to the wavelengths of interest here. The QW region consisted of 75 periods of 65 Å GaAs wells and 50 Å Al<sub>0.3</sub>Ga<sub>0.7</sub>As barriers, giving a total thickness of 0.86 μm. The doped regions ( $n, p \approx 10^{18} \text{ cm}^{-3}$ ) had thicknesses of 0.9 μm each. Using conventional photolithography and lift-off techniques,<sup>4</sup> contacts were made to the doped regions, with 200 μm × 200 μm optical windows on the *p* side. The samples were antireflection coated, the substrate was removed with a selective etch,

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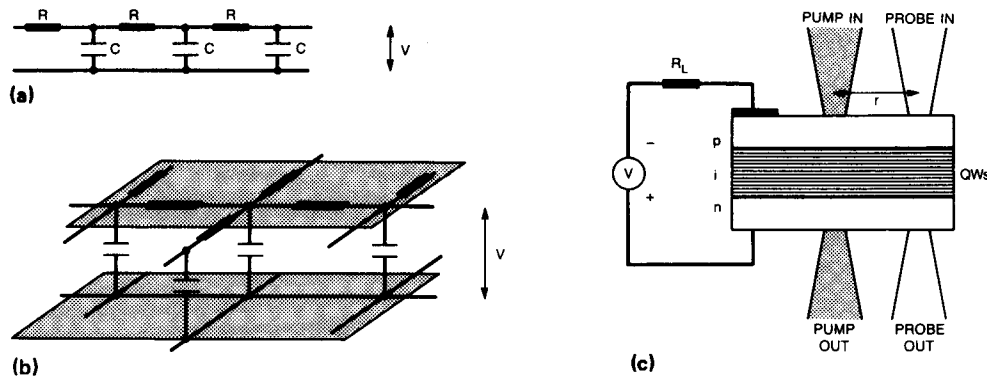


FIG. 1. Schematic model of (a) a dissipative transmission line and (b) surface, used here to describe the propagation of the photoexcited electrical signal in the *p-i-n* structure. (c) Biasing circuit and geometry used in optical experiments.

and the resulting device was glued to a sapphire disk.

As can be seen from Fig. 2, the absorption spectrum of the sample contains the typical excitonic peaks at the  $n = 1$  absorption edge, corresponding to transitions involving the heavy and light hole, respectively. As the applied electrical field is increased, the whole spectrum shifts to lower energies and slightly broadens. For  $\lambda = 838.5$  nm (dashed line in Fig. 2) and around 15 V bias, the change in transmission is approximately linear with the voltage reduction.

The setup used for the optical measurements is typical for pump-and-probe experiments.<sup>5</sup> The short laser pulses (6–10 ps) were obtained using a Styryl 9 dye laser (tunable between 780 and 870 nm), synchronously pumped with a mode-locked Kr ion laser (80 MHz repetition rate). The infrared laser beam from the dye was split into two beams, time delayed from each other. The powers of the two beams could be controlled separately, with the probe beam power being a few percent of that of the pump. The exciting beam power ranged between 0.1 and 1 mW (1.2–12 pJ per pulse). The two beams (incident under a slight angle) were focused on the sample to spots varying between 25 and 160  $\mu\text{m}$  diameter [Fig. 1(c)]. The changes in the intensity of the transmitted probe were detected using standard lock-in techniques. The measurements were done at room temperature.

Photoexcited carriers (electrons and holes) are created instantaneously in the QWs, and their first effect is some instantaneous bleaching of the absorption.<sup>6</sup> Without an electrical field these carriers can have a lifetime of the order of

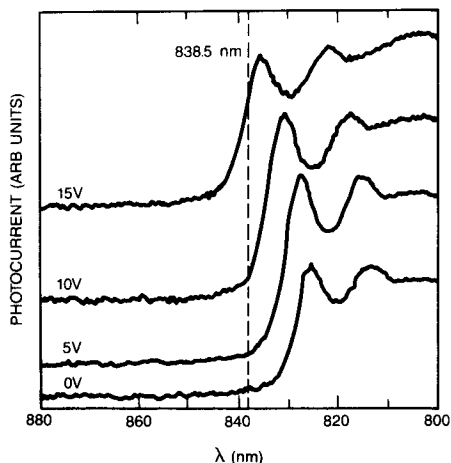


FIG. 2. Photocurrent spectra as a function of the applied electrical field. The pump-and-probe measurements reported here were done at  $\lambda = 838.5$  nm (dashed vertical line).

many nanoseconds, whose consequence is a slow decay of the bleaching of the absorption. In the presence of an applied electrical field the carriers are separated from each other and attracted towards the electrodes. Either by a tunneling process<sup>7,8</sup> or by thermionic emission,<sup>9</sup> the carriers escape from the wells and transport to the electrodes, thereby locally reducing the voltage and changing the absorption coefficient through the QCSE (see Fig. 2). We may expect a much larger change in absorption (for the same created charge) from the QCSE than from the instantaneous bleaching. The processes related to the escape of carriers from the quantum wells and to their vertical transport occur on time scales of the order of 1–100 ps, and are responsible for the rise time of the signal in our experiments. The decay time of the signal has to do with the recovery of the initial electrical field in the structure, which is the mechanism we will concentrate on. Actual carrier diffusion can play little role in our experiments; even traveling at saturated drift velocities  $\sim 10^7$  cm/s, the carriers can only travel  $\sim 1$   $\mu\text{m}$  in 10 ps, resulting in movements much smaller than our beam sizes.

An example of the time-resolved data we obtain is shown in Fig. 3. These curves represent a series of measurements taken at an applied voltage of 15 V, with  $\lambda = 838.5$  nm, using small spots (25  $\mu\text{m}$  diameter), and varying the distance  $r$  between the pump and the probe spots on the sample. The average pump power was 100  $\mu\text{W}$ , chopped at 1.2 kHz, the probe power was 5  $\mu\text{W}$ .

Concentrating first on the top curve (overlapped spots), we observe a large positive lock-in signal, as expected for a reduction in voltage. A careful calibration of the lock-in signal indicates that, in the conditions of Fig. 3, a voltage modulation of 2 V produces a lock-in signal of +8 mV, and a change in transmission of about 25%. Similar data were obtained at other wavelengths and voltages, with the sign of the signal always corresponding to  $\Delta V < 0$ . The rise times ranged from 20 to 100 ps; the decay times were of the order of several hundreds of picoseconds. As we move down in Fig. 3, we see the response as the probe spot is separated from the pump. The resulting transmission changes are delayed relative to the pump and are progressively smaller, as would be expected from our diffusive conduction model [Eq. (2)].

To test the model quantitatively, we fitted the whole set of experimental curves in Fig. 3 using Eq. (2) and only one set of parameters. We allow a finite time for the carriers to leave the wells and arrive at the electrodes; for this we assumed a simple exponential emission rate of time constant  $\tau$ . We also allowed for the finite measured pulse width  $\Delta$  of the

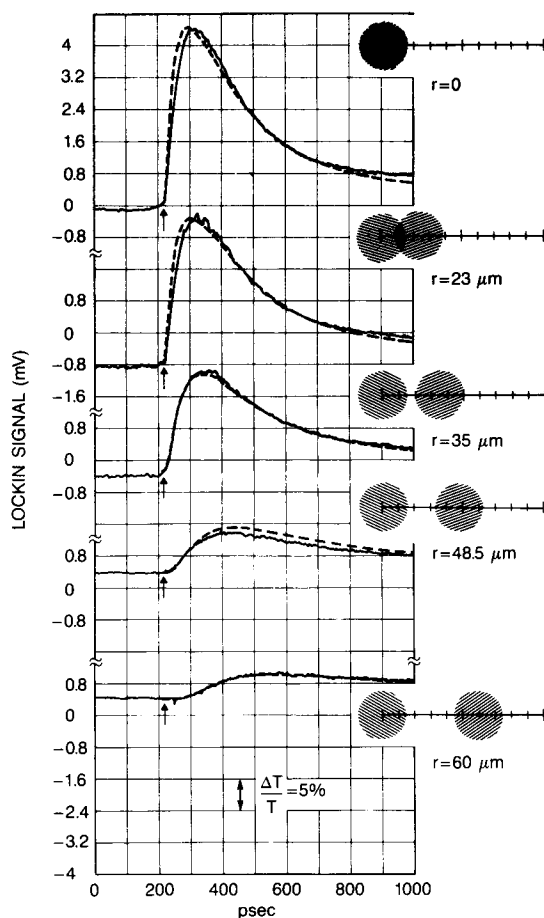


FIG. 3. Illustrative time-resolved results, as a function of the separation  $r$  between the pump and the probe spots ( $\lambda = 838.5$  nm and  $V = 15$  V). The lock-in signal is proportional to the change in transmission,  $\Delta T$ , which in turn is a measure of the change in voltage,  $\Delta V$ . Full curves: measured. Dashed curves: calculated, using a single set of parameters.

laser in the generation rate of carriers, and we assumed for simplicity that the absorption was uniform through the depletion region. The finite spot size of the probe beam also necessitates some spatial convolution, but this is simple and was done analytically, assuming both beams to be Gaussian. For the resulting theoretical curves in Fig. 3, we fitted  $\tau$ ,  $D$ , and  $V_M$ , obtaining  $\tau = 110$  ps,  $D = 0.8 \times 10^5$  cm<sup>2</sup>/s, and  $V_M = 25$  V. This agrees well with our calculated  $D \sim 10^5$  cm<sup>2</sup>/s, based on the sample doping concentrations, layer thicknesses, and dielectric constant. The order of magnitude of  $\tau$  agrees with data obtained by other authors from time-resolved photoluminescence measurements,<sup>7,8</sup> from the high-frequency response of QW  $p$ - $i$ - $n$  photodetectors,<sup>9</sup> or from the pump-and-probe experiments similar to ours, very recently published by Manning *et al.*<sup>10</sup> The vertical normalization used in the fit,  $V_M = 25$  V, represents the total voltage change that would have occurred, were the photoexcited charge instantaneously created on the electrodes. Our estimated value, based on the measured responsivity and optical powers, is  $V_M = 18$  V. Of course, in the actual experiment the peak transmission change corresponds to only  $\sim 2$  V. This is because the voltage pulse propagates away rapidly as soon as we start to deposit the charge; the characteristic time for diffusion, corresponding to the fitted  $D$  and measured spot radius here ( $15 \mu\text{m}$ ), is  $\tau_c = 5$  ps, much faster

than the time  $\tau \sim 110$  ps for the charge to be delivered to the electrodes. If the charge did transport instantaneously to the electrodes, the resulting recovery of the QCSE absorption change would be very rapid ( $\sim 5$  ps).

As a further check on the model, we repeated the experiment with a very large pump spot ( $160 \mu\text{m}$  diameter). In this case, we still saw finite rise times, but essentially no decay over many hundreds of picoseconds as expected from our model: for this large pump spot, the calculated  $\tau_c$  is 400 ps. Furthermore, in this case, the measured change in transmission was consistent with the full  $V_M$  being generated in the sample. This experimental configuration also allows a more direct measure of  $\tau$ : we have seen rise times  $\tau \sim 30$ – $100$  ps under a variety of voltage and sample conditions.

The effective speed of the diffusive propagation can be varied by altering either the spot size or the resistivity or thickness of the layers. For example, for this sample we estimate  $\tau_c = 25$  fs for  $w_0 = 2 \mu\text{m}$ ; of course the transport of the carriers out of the wells is so much slower that no dynamics on this time scale could be seen, but the actual consequence would be that almost no voltage would build up, and there would be almost no local QCSE-induced change in absorption from the created carriers because the diffusion would be so rapid. By using spots of  $1.8 \mu\text{m}$ , we indeed measure extremely small changes in transmission:  $\Delta T < 1\%$ .

In conclusion, we have identified a novel, fast mechanism for the local recovery of optical absorption in biased QW diodes. This "diffusive electromagnetic propagation" operates much faster than actual carrier diffusion or recombination, and depends only on the resistivities and thickness of the sample layers, and the optical spot size. The resulting diffusive time scale could be controllably varied over many orders of magnitude. We have also seen evidence of the finite times associated with carrier emission and transport perpendicular to the layers, and this will be the subject of further study.

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<sup>3</sup>For a review of QW electroabsorption physics and devices, see D. A. B. Miller, D. S. Chemla, and S. Schmitt-Rink, in *Optical Nonlinearities and Instabilities in Semiconductors*, edited by H. Haug (Academic, Orlando, 1988), pp. 325–359.

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