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High-Speed Quantum Well Optoelectronic Gate Based on Diffusive Conduction Recovery

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Abstract
A novel high-speed optoelectronic gate, based on electric field screening and ultrafast electrical recovery, is proposed, and demonstrated in principle with ultrathin barrier quantum wells.

High-speed optical gates (operating, for example, on a picosecond time scale) are highly desirable for ultrafast information processing, such as in time-domain multiplexed networks and telecommunications. Nonlinear optical gates can give the necessary speed, but often take too much energy or power, and are not conveniently integrable with silicon electronics for control or information read-out. Optoelectronic devices can be conveniently small and readily interfaced with electronics, but are often slowed down by the finite speeds of electrical connections. Here we propose a novel optoelectronic device that can run with low optical energies, can be integrated readily with electronic information processing, and avoids the usual speed limitations of electrical connections. We also show preliminary data from a first such device.

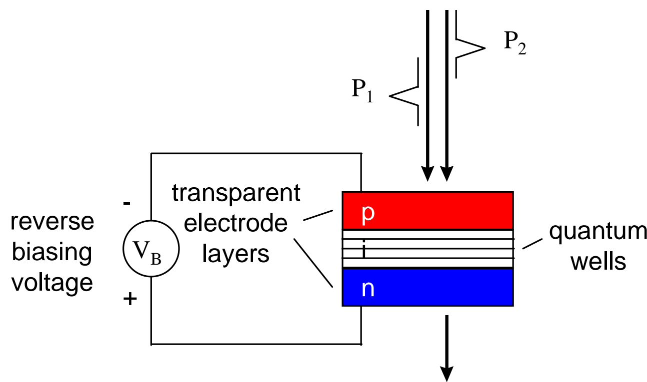

Fig. 1 Illustration of the reverse biased quantum well diode, with the first (P_1) and second (P_2) short light pulses used in operation.

The concept of the device is illustrated in Fig. 1.
A quantum well diode is reverse-biased with a fixed external voltage, V_B. A first optical pulse, P_1, which we can regard as a "signal" or "gating" pulse depending on the mode of operation, is absorbed in the device. The electrons and holes generated inside the quantum well region leave the quantum wells and are transported to the *p* and *n* electrodes. As they move towards the electrodes, these carriers screen the applied electric field inside the device. As a result, the optical absorption of the quantum wells is changed through the quantum-confined Stark effect [1]. The second pulse, P_2, therefore sees a different absorption in the device if it arrives at an appropriate time later. If the recovery of the gate is also fast, this device can be used as a time-sensitive gate; the second pulse is strongly transmitted only if it arrives within a short time window after the first pulse, as might be exploited in a time-demultiplexing device. The device can also operate as a logic AND gate; only if the two pulses arrive (in the correct timing sequence) is the second pulse transmitted. The amount of photocurrent generated by the absorption of the second pulse will be sensitive to the time of arrival of the second pulse, so the device can operate as a gated photodetector. It should also be possible in the device to use a weak first pulse to gate a stronger second pulse, so the device may be able to show signal gain. This gain is possible because a pulse, if shorter than the carrier escape and transport time, has relatively little effect on itself, with its electrical effects growing after it has been absorbed.

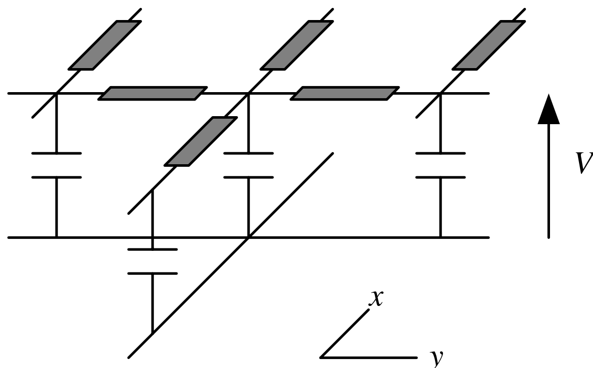

Fig. 2. Conceptual mesh of resistors and capacitors for analysis of the diffusive conduction

Normally, the objection to such a device would be that, although the gating can be turned on rapidly, the turn-off time would be long, perhaps corresponding to the external resistive-capacitive time constant of the entire device. However, there is another process that can be exploited to relax the voltage change controllably on a very short time scale. This process is diffusive electrical conduction [2]. The concept of this mechanism is illustrated in Fig. 2.

The p and n regions of the diode can be considered as the resistive plates of a capacitor, and can be modeled as a mesh of resistors with capacitance between the top and bottom layers. (for simplicity in Fig. 2, resistance is shown only in the top layer; in fact, this is also a valid approach for analysis since the combined resistance of top and bottom layers can be summed into the resistance in one layer without changing the results.) In such a mesh, if the voltage is changed locally on the mesh by injecting charge into some of the capacitors, the voltage can relax through the local electrical conduction in the resistors. If we analyze such a mesh, we conclude that the voltage obeys the following equation

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

which has the same form as a diffusion equation. (Incidentally, it is important to understand that this does not represent the diffusion of the actual carriers generated, but is rather a dissipative electrical wave propagation that can actually be much faster than the physical movement of individual carriers.) The effective diffusion constant, D, is given by

$$D = \frac{1}{R_S C_A}$$

where R_S is the sum of the resistances per square of the top and bottom conducting layers, and C_A is the capacitance per unit area.

In the optical case the lateral shape of the injected charge distribution is initially approximately Gaussian because of the Gaussian optical beam shape, which results in a particularly simple analytic formula for the local voltage change as a function of time t and radius r from the center of the beam,

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

where

$$\tau_{rel} = w_o^2 / 8D$$

and

$$V_M = 2Q_{tot} / \pi w_o^2 C_A .$$

Here Q_{tot} is the total charge created (on each capacitor plate) by the absorbed photons, and w_o is the $1/e^2$ intensity radius of the Gaussian beam. Fig. 3 illustrates the Gaussian voltage change as a function of time.

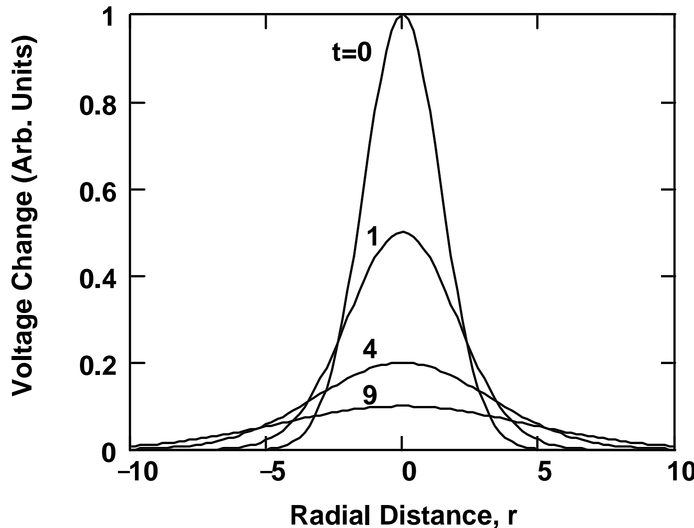

Fig. 3. Illustration of relaxation of the initial Gaussian voltage distribution in diffusive electrical conduction from an initial Gaussian voltage distribution on the conducting capacitor plates at time $t = 0$. Curves are shown for times $t = 0$, 1, 4, and 9 units. Time is in units of the characteristic time, τ_{rel}. Distance is in units of the initial Gaussian spot radius, w_o.

The absorption of photons in the quantum well layers, and the subsequent separation of the electrons and holes in the electric field, therefore leads to a voltage reduction laterally in the p and n regions that is approximately Gaussian in shape. In time, the Gaussian grows spatially, reducing the magnitude of the voltage change as it spreads, effectively relaxing the voltage change locally, and returning the device to its original condition. The generated charge does eventually move through the external circuit, but the local voltage can be relaxed on a timescale much faster than this external charge movement. The characteristic time for this local voltage recovery is τ_{rel}, which in practice depends on the resistivity of the p and n layers and the spot size w_o. Hence, in this device, the turn-on time is controlled by the emission and separation of charge from the quantum wells, and the turn-off time is controlled by the diffusive electrical conduction. Both of these times can be controlled in the picosecond region, allowing an optoelectronic gate that can operate on this timescale.

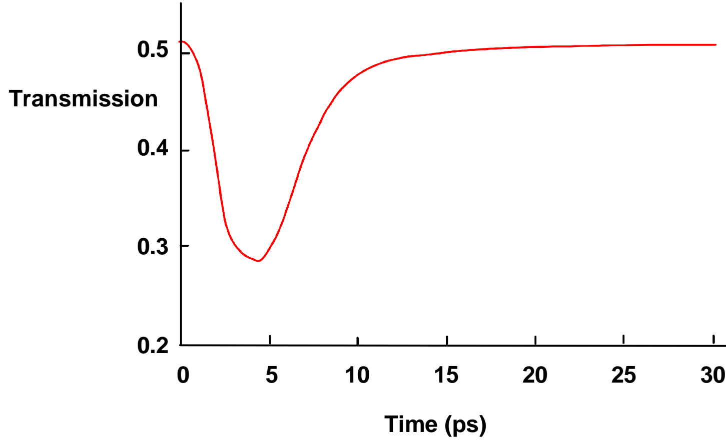

Fig. 4. Simulation for the shallow quantum well sample of Refs. [3] and [4], with τ_{rel} ~ 5.6 ps, V_M = 13 V, V_B = 5 V reverse bias.

An additional important feature of this device is that it can be very sensitive compared to "all-optical" processes such as absorption saturation. The reason for this sensitivity is that the charge generated in each well eventually contributes to screening in all the wells once the charges have transported to the electrodes. To take the simplest case, suppose the carriers leave all the wells and gather at the electrodes. Then, for *n* wells altogether in the structure, we will get the field screening corresponding to *n* times as many carriers compared to the case of in-well screening. (Note that the field between two sheets of charge depends only on the total charge density in the sheets, not on the separation of the sheets.) For example, suppose there are 50 wells in the structure. The *total* number of carriers per unit area required for 5 x 10^4 V/cm field change (which is large enough to cause significant electroabsorptive change of transmission) is about 3 x 10^{11} cm^{-2}. To achieve this total density, we require only an average of about $1/50^{th}$ of that to be initially generated in each well, i.e., ~ 6 x 10^9 cm^{-2}, requiring an incident optical energy of about 2 fJ/μm^2 instead of the > 100 fJ/μm^2 needed for in-well screening or a nonlinear optical process such as excitonic saturation. Hence, compared to excitonic absorption saturation or in-well screening, we have a nonlinear effect at least 50 times stronger in terms of the energy required to cause the nonlinear response.

Fig. 4 shows a simulation of the operation of a such a device based on meadured absorption data for a shallow quantum well [3], a structure that has also been demonstrated to have fast carrier escape and transport [4].

In the operation of the device, the processes of the escape and transport of carriers, which generate local voltage changes on the device, are happening at the same time as those voltage changes are starting to relax by diffusive conduction, so the resulting simulated response represents a convolution of the diffusive conduction relaxation "response" with the charge escape and transport "drive".

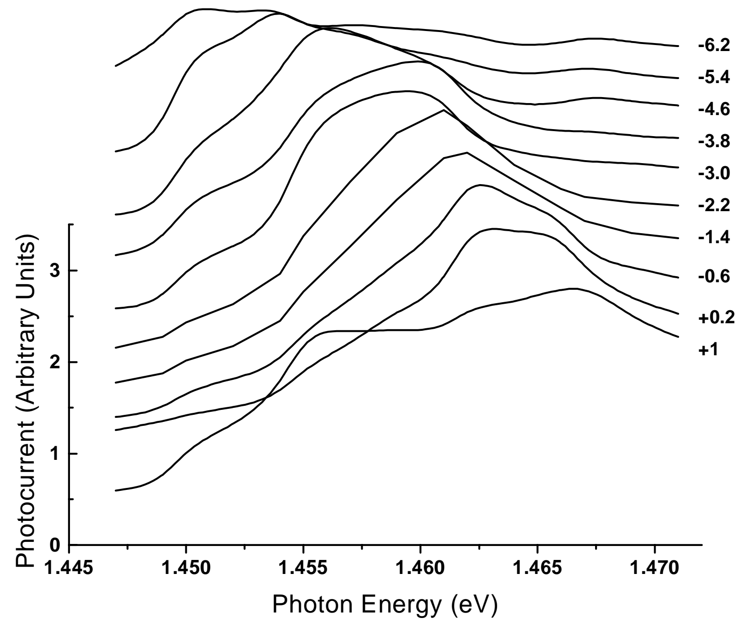

Fig. 5. Photocurrent spectra for various biases, from 1 V forward bias to 6.2 V reverse bias. spectra are vertically displaced for clarity.

The shallow quantum well design simulated above could be attractive for the operation of this device, but the shallow quantum well electroabsorption has a relatively narrow spectral region of operation as a strong effect, and, though a particularly sensitive electroabsorption, is limited in the total absorption change. It is, however, necessary to choose a quantum well design that has relatively fast carrier escape. The common quantum well designs with moderately thick (e.g., 3.5 nm) medium-high (e.g., $Ga_{0.7}Al_{0.3}As$) barriers round GaAs quantum wells (e.g., 9.5 nm thick), leads to moderately fast carriers escape times (e.g., 30 - 100 ps [5] at fields up to 6 x 10^4 V/cm) that, though fast, are not fast enough for our desired

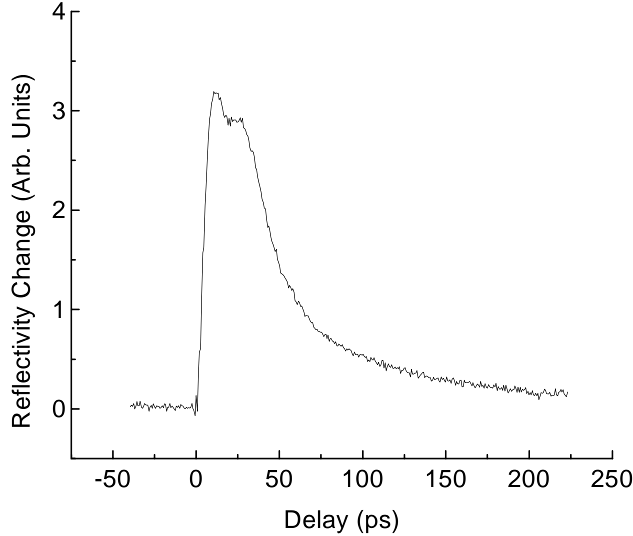

Fig. 6. Change in probe reflectivity as the probe beam (P_2) is delayed relative to the pump beam (P_1). Pump power is 23 µW, probe power 1.3 µW, wavelength 854 nm, spot diameter 22 µm, reverse bias, V_B, 5.8 V

picosecond operation. We have therefore chosen to investigate a novel quantum well design, using very thin (0.5 nm) high (AlAs) barriers together with a conventional 10 nm GaAs quantum well, with the goals of extracting carriers rapidly through tunneling while retaining a strong electroabsorption. The use of thin barriers also means that a larger number of quantum wells can be packed into a given thickness, which itself gives stronger absorption effects. A consequence of using such thin barriers is that there will likely also be strong quantum-mechanical coupling effects between the wells, though this need not necessarily prevent the underlying electroabsorption mechanisms.

The test sample was designed as a reflective (rather than transmissive) structure, starting with a $Ga_{0.68}Al_{0.32}As$/AlAs multilayer quarter-wave dielectric stack mirror grown on a GaAs substrate, and *n*-doped with Si at concentrations between 6.3 x 10^{17} cm^{-3} and 2 x 10^{18} cm^{-3}, followed by 100 undoped quantum well periods, a 1 micron thick $Ga_{0.68}Al_{0.32}As$ *p* layer Be-doped at 10^{18} cm^{-3}, and a 10 nm thick GaAs contacting layer doped at 2 x 10^{19} cm^{-3}. Contacts were taken off the top of the test device structures and off the substrate, and the devices themselves were ~ 200 micron square mesas.

The electroabsorptive behavior of this device is given in Fig. 5, which shows photocurrent spectra. The spectra show what is likely Wannier-Stark localization as the device is brought from moderate forward bias to approximately 0V bias, followed by a predominant quantum-confined Stark effect shift of the lowest energy peak to lower photon energies. There are also various weak transitions and level anti-crossings observable in the structure, which are likely due to coupling of levels between adjacent wells. Despite the clear appearance of coupling-induced effects, the structure appears to show strong electroabsorption suitable for modulation.

For preliminary tests of the device concept, we used this structure to test for fast carrier escape and diffusive conduction behavior. We see evidence of both, and observe operation of the device in principle. For these experiments, a mode-locked Ti:sapphire laser, producing ~ 1.7 ps pulses at ~ 80 MHz repetition rate, was used in a standard pump-probe configuration. Fig. 6 shows the reflected probe power as a function of its delay relative to the pump beam. There is a clear rapid rise of the transmission that we expect is caused by the carrier escape and transport, followed by a relatively rapid decay of the signal as expected from diffusive conduction. Experiments are continuing to verify the detailed operation of the device and the optimum design and operating conditions.

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