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Time resolved measurements of cross-well transport in a multiple quantum well *p-i-n* modulator at high photogenerated carrier densities

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Carrier sweep-out rates from GaAs/AlGaAs multiple quantum wells have been measured as a function of excitation level on picosecond time scales at different values of applied electric field. A minimum rate of ~ 20 ps was observed under resonant tunneling conditions at low generated carrier densities. At higher excitation levels, the effects of space charge build-up were found to significantly alter the transient nonlinear optical response due to changes in the time constant associated with vertical carrier transport.

A number of multiple quantum well (MQW) optoelectronic devices such as photodetectors, optical logic elements, and lasers depend on cross-well carrier transport for their operation. For instance, the self-electro-optic effect device (SEED), consisting of MQWs positioned within the intrinsic region of a *p-i-n* doped structure,¹ functions simultaneously as an optical modulator and photodetector. The ultimate speed of this device will be determined by the rate at which photogenerated carriers can be ejected from the quantum wells to establish the cross-well photocurrent, while modulation at high frequencies will be limited by any space-charge build-up of the carriers. In this paper, we describe time resolved pump-probe measurements in a MQW SEED structure under excitation conditions in which the effects of space-charge build-up and absorption saturation on the transient properties of the SEED device are important.

The details of cross-well carrier transport in reverse biased MQW structures can be very complex. Carrier escape from the wells may take place by thermionic emission or tunneling, or a combination of both depending on the local field conditions. Cross-well carrier transport rates can be optimized for specific applications by appropriately designing the structure and by choice of operating conditions. For instance, Boyd *et al.*² have achieved a switch-on time of around 30 ps in symmetric SEED devices, while LiKamWa *et al.*³ have reduced the recovery time of an all-optical MQW waveguide directional coupler switch to around 100 ps by employing cross-well carrier sweep-out.

A number of papers⁴⁻⁸ have reported low excitation level, picosecond pump-probe measurements in MQW *p-i-n* structures which have time resolved the electron emission rates from the wells as a function of electric field. Resonant tunneling is identified by the observation of a minimum in the rise time of the signal at specific applied voltages which depend on the MQW design.^{2,7} At higher excitation levels appropriate to the operating conditions of SEED and other nonlinear optical switching devices, absorption saturation and space-charge build-up can become significant. The effects of absorption saturation in electrically biased MQWs have been studied under steady state

conditions by Wood *et al.*⁹ and Fox *et al.*^{10,11}

The MOVPE grown *p(i-MQW)n* sample used in these studies consisted of an intrinsic region ~ 1 μm thick comprising 87 Å wide GaAs wells and 60 Å wide $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x = 0.3$) barriers. The substrate was removed by selective etching and the sample mounted on a sapphire substrate. A ~ 200 μm window on the *p* side allowed light to pass perpendicular to the wells. An external dc reverse bias electric field was applied perpendicular to the QW layers via contacts made to the doped regions. Transmission spectra of the sample at three different applied voltages are shown in Fig. 1. In the absence of the applied field, the positions of the exciton absorption resonances appeared at 847 nm (heavy hole) and 840 nm (light hole). (Some additional modulation in transmission at longer wavelengths is caused by Fabry-Perot effects.) With increasing reverse bias voltage, the whole band edge transmission shifts to longer wavelengths, with the exciton valleys remaining resolved.

A mode-locked and cavity dumped styryl 9 dye laser (Coherent 702), synchronously pumped by a mode-locked, frequency doubled Nd:YAG laser (Coherent Antares) produced ~ 1 ps pulses tunable between 820 and 870 nm. A conventional pump-probe arrangement was employed with both beams focused onto the sample by a single 10 cm focal length antireflection coated lens. Both beams had ~ 35 μm (FWHM/e^2M) spot sizes on the sample. Cavity dumping reduced the repetition frequency to 7.6 MHz thus avoiding pulse-to-pulse charge accumulation since the carrier recombination time is on the order of 10 ns. The pump beam was mechanically chopped at 1 kHz and the probe signal monitored using phase sensitive detection. Changing the external circuitry had no effect on the measured transients, i.e., the transmission changes occurred on time scales shorter than the bias circuit response time.

Transmission changes measured as a function of probe delay are shown in Fig. 2 for several reverse bias voltages under conditions of relatively low excitation level (8 pJ per pump pulse producing on the order of $5 \times 10^{10} \text{ cm}^{-2}$ electron hole pairs). The dc bias causes a red shift of the absorption edge via the quantum confined Stark effect (QCSE). The laser was tuned to the long wavelength side of the exciton resonance and measurements made at the

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FIG. 1. Transmission spectrum of MQW pin modulator (CPM405) under three reverse bias conditions.

wavelength corresponding to the maximum transmission change for each applied voltage. The rise in signal, $\Delta T(t)$, results from the blue shift of the exciton as the photogenerated electrons and holes leave the wells and move toward opposite doped regions. The charge separation screens the applied field and hence reduces the exciton shift produced by the QCSE. The rise time of the signal therefore gives a measure of the rate that the carriers escape from the quantum wells to establish a photocurrent. The subsequent fall in signal is caused by transverse diffusive conduction of carriers once they reach the doped regions thus restoring the original field.⁶ The data was fitted to rising and falling exponential functions to determine rise times, t_r and decay times t_d :

$$\Delta T(t) = \Delta T_{\max} [1 - \exp(-t/t_r)] \exp(-t/t_d).$$

(An exponential decay gave a better fit to the data at the longer delays employed in these measurements compared to the two-dimensional diffusive conduction model of Livescu *et al.*⁸). These processes all take place on time scales significantly shorter than the carrier recombination time and the response time of the external circuit.

The signal rise times t_r are plotted in Fig. 3 as a function of dc bias. At low voltages, when the escape of electrons from the wells is dominated by thermionic emission, the rise time is around 500 ps. Above 2.5 V, the rise time decreases and gives a minimum of around 20 ps at 5 V.

FIG. 2. Pump-probe measurements at different reverse bias applied voltages at low pump power (63 μ W average power at 7.6 MHz).

FIG. 3. Rise time t_r as a function of applied voltage at low pump powers. (Inset illustrates the effect of increasing electrical bias on the cross-well transport.)

This reduction is due to the addition of tunneling to the emission process. The minimum value occurs under conditions of resonance between the $n=1$ level of one well and the $n=2$ level of the adjacent well. For voltages above resonance, the rise time increases to ~ 130 ps before falling again when tunneling is possible from the $n=1$ level directly into the continuum. Above 10 V this time constant reduces to the transit time for carriers across the 1 μ m wide intrinsic region. The largest signal is measured on resonance at 5 V when the carriers are rapidly ejected from the wells allowing a larger density to accumulate in the doped regions. At high fields, the magnitude of the signal is reduced due to broadening of the exciton feature thus decreasing the maximum transmission change.

Transmission changes as a function of delay time $\Delta T(t)$ are shown in Fig. 4 for larger pump power levels at three different applied voltages. The three voltages chosen are (a) 3 V, below resonant tunneling conditions, (b) 5 V, on resonance, and (c) 7 V, above resonance. At the higher pump levels, the time dependence of the transmission is much more complex. For instance, at 5 V, a transmission change as large as 30% was recorded with two time constants evident in the rising edge, while the time scale for the decay of the signal increases and is no longer a simple exponential. The initial fast rise in transmission and the large total transmission change is consistent with exciton absorption saturation at carrier densities in excess of 10^{11} cm^{-2} . The slower component of the rise can be attributed to screening of the dc field and the corresponding blue shift as observed for low excitation. At higher excitation levels, the large generated carrier densities results in an appreciable cancellation of the applied field. The consequences of this are observed more clearly in the signal decay rather than the rise. We do not expect the transverse diffusion process to be density dependent. Thus, we interpret the slower recovery at high carrier densities as a reduction in the emission rate for the carrier from the quantum wells when the field is effectively screened by the space charge. The carrier escape rate therefore limits the decay rate of

FIG. 4. Pump-probe measurements at three different voltages, (a) 3, (b) 5, and (c) 7 V, and at different average pump power levels, (1) $63 \mu\text{W}$, (2) 0.63 mW , (3) 1.0 mW , and (4) 2 mW .

the signal. A reduced local field corresponds to a shift to the left for the conditions plotted in Fig. 3. In the case of a dc bias of 5 V, when the initial carrier escape time constant is on the order of 20 ps, the carrier emission time may slow by over an order of magnitude as the screening reduces the local fields. At 3 V, the difference in decay time at high as compared with low excitation levels is not so evident because the initial conditions start from a slower carrier emission rate. On the other hand, at 7 V the high excitation results again give a slower recovery than at low level, however the overall recovery is faster than for the 5 V case

since screening moves the device through resonant tunneling conditions.

In conclusion, we have identified the consequences of screening of the applied electric field at high photogenerated carrier densities in a MQW SEED device by space-charge build-up on picosecond time scales. In a device which shows a 20 ps time constant for the establishment of the photocurrent under conditions of resonant tunneling, the recovery time was found to increase to several nanoseconds at carrier excitation levels above 10^{11} cm^{-2} . Higher bias voltages provide a more rapid carrier sweep-out and faster overall response time. These effects are important to take into account when designing high speed SEED devices, MQW directional coupler switches, and QCSE optical modulators capable of handling high optical powers. The ultimate clock rate or upper frequency limit will be determined by the rate that photogenerated carriers can be swept from the wells. Due consideration must be paid to the design of the quantum well structure. Recent reports of extremely shallow wells may circumvent these high carrier density effects because of the very fast carrier emission rates achievable in these devices at all applied voltages.¹²

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