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Optically-Controlled Optical Gate Using a Double Diode Structure

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Abstract: **A new device concept enabling ultra-short optically controlled optical gating is demonstrated. Using a dual-diode GaAs multiple-quantum well (MQW) structure, low power surface-normal switching times of ~10 ps are achieved in this proof-of-principle device.**

Introduction:

Controlling optical data streams has grown in increasing importance in recent years as fiber optics, telecommunications, and the Internet have gained tremendous popularity. A variety of methods are being pursued to encode, decode, and switch optical data, from all-fiber technologies to electronic detection and re-transmission. We recently presented a novel optoelectronic device, an optically-controlled optical gate, able to control optical reflection or absorption on a 50 ps time scale with low optical control energies (e.g. <1 pJ).[1] This previous device used multiple quantum wells (MQW) in a p-i(MQW)-n structure, and relied on internal diffusive conduction to provide fast recovery. The device speed was limited, however, by carrier escape from the quantum wells.

We introduce here a new device concept: a double p-i-n structure to remove the previous speed restrictions by using different diodes for the control and modulation functions. The control diode does not use quantum wells, allowing very fast switch-on time limited only by carrier transport in a conventional bulk semiconductor layer. Switch-off times remain controlled by high-speed internal diffusive conduction.[2] This should enable picosecond switching times. Such a device might be used in a number of different systems, including time-division multiplexing and demultiplexing, gated photodetection, and analog-to-digital conversion.

Theory of Operation:

The dual-wavelength optically-controlled optical gate consists of a p-i-n diode sitting on top of a p-i(MQW)-n diode (Fig. 1). The top diode is designed so that it is transparent to the signal pulse (approximately 850 nm) while strongly absorbing at the shorter control pulse wavelength. The bottom diode's MQW region is sensitive to the signal wavelength, and beneath it sits an integral distributed Bragg reflector (DBR) mirror, enabling the reflection of the signal. The device opens and closes its reflection gate in a series of three steps: (1) Both the bottom and top diodes are reverse biased, the former so that the signal is not strongly absorbed (i.e. highly reflecting, with photon energy just below the exciton absorption peak). This is the "off" state of the device. (2) The control pulse reaches the device. It is fully absorbed in the top diode, primarily in the intrinsic region and hence creates electrons and holes. The electrons and holes separate due to the reverse bias, shielding the bias as they separate. This change in voltage in the vicinity of the spot size is limited only by the transport times of carriers in the bulk material,

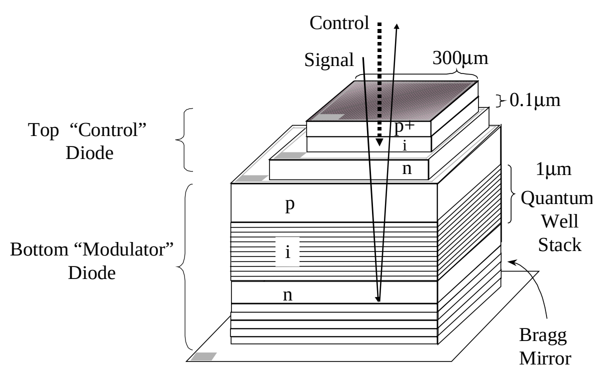

Fig. 1: Device schematic of a double diode structure with an ITO deposition over a thin top diode (100 nm intrinsic region) and a p-i(MQW)-n bottom diode.

which may be ~1 ps in this thin layer. In the simplest model for this device, we presume the top and bottom layers of the entire structure are very highly conducting and consequently the voltage across them is kept constant. Hence, any reduction in voltage locally in the top diode is balanced by an opposite voltage change locally in the bottom diode, thus altering the absorption of the bottom diode – and as such, also the reflectivity. The device is now "on". (3) The local voltage change relaxes, limited by conduction in the more resistive central n and p layers through a fast local process that can be described as diffusive conduction, a process that can operate on a picosecond time scale.[2] Combining these three steps, the device should be able to turn "on" and "off" in picoseconds. Device repetition rate, addressed elsewhere,[1] in theory should be limited only by this on-off cycle and not external RC time constants.

Design and Fabrication:

The specific MBE-grown structure sits on an n-doped GaAs substrate and begins with an n-doped DBR stack centered about 850 nm that consists of 20 pairs of alternating AlAs and $Al_{0.3}Ga_{0.7}As$, followed by a MQW intrinsic region with 60 pairs of 120 Å GaAs wells and 40 Å AlAs barriers and a 1 µm p-doped $Al_{0.3}Ga_{0.7}As$ layer. Above this bottom diode an n-region 500 nm thick, a 100 nm intrinsic region, and finally a 50 nm p-layer were grown (all of $Al_{0.3}Ga_{0.7}As$), forming the top diode. To increase the conductivity of the top p-layer, 660 nm of indium-tin-oxide (ITO) was deposited and annealed (500^{o} C, 5 minutes); this layer also acted as an anti-reflection coating. A four-layer structure was etched away, allowing ring contacts to be deposited on each p and n layer, with the central square mesa structure 300 µm wide.

The experiment was conducted using a standard pump-probe set-up using ~150 fs pulses from a *Tsunami* Ti-Sapphire laser operating at an 82 MHz repetition rate. In order to obtain a control (pump) pulse of a different wavelength than the signal (probe) pulse, a BBO crystal (1 mm thick) was used to generate second-harmonic pulses at 428 nm. Photocurrent measurements demonstrated that indeed the control pulses were fully absorbed in the top diode while the signal pulses were absorbed only in the bottom diode.

Results:

Our results for this proof-of-principle device are shown below (Fig. 2). A 300 µW, 428 nm control beam with 600 fJ energy absorbed in the top diode per pulse, and a 20 µW, 857 nm signal beam pulse train were used with beam diameters of about 20 µm. The top diode was biased at –4.0 V and the bottom diode biased at –2.7 V. A curve-fit to the data indicates a diffusive conduction time constant of 6ps for the device. We estimated a 4-5 ps diffusive conduction time constant based on the nominal dopings of the structure, which is in good agreement given the possibility that not all the dopants may give free carriers due to possible deep levels in the $Al_{0.3}Ga_{0.7}As$ structure.[3]

Other limiting factors that this initial device displays include the ITO, which absorbs over half the incoming light. Also, chromatic aberration of the lens system limited spot-size reduction.

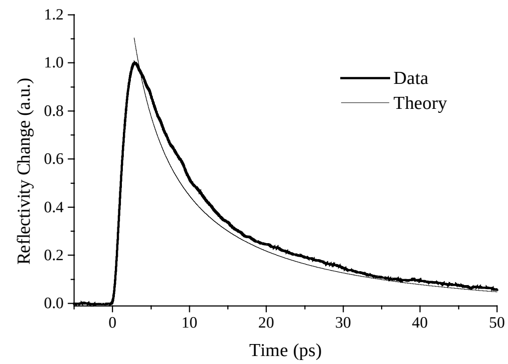

Fig 2: Reflectivity data and theoretical fit to 6 ps diffusive conduction time constant. Gate opens and closes with a 9.3 ps FWHM creating a 10% change from initial reflectivity.

Conclusion:

We have demonstrated a new device concept: a dual-wavelength, surface-normal optically-controlled optical gate based on diffusive conduction, which is able to open and close its reflectivity gate in 9.3 ps FWHM using 600 fJ absorbed energy. Future work includes improving the ITO deposition layer to increase its conductivity while reducing its absorption, optimizing the bottom diode for low-voltage and wide-bandwidth operation, tailoring the diffusive conduction time constants to improve device speed, and reducing the spot size to improve efficiency. This work was supported by the U.S. Department of the Army, Army Research Office.

References:

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