Demonstration of an Optoelectronic Dual-Diode Optically Controlled Optical Gate with a 20 Picosecond Repetition Period

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Abstract: Using surface-normal pulses, a low-power, optically controlled optical gate incorporating two stacked AlGaAs diodes opens and closes within 20 picoseconds with a 30% reflectivity change. Repeated gating with 20 picosecond periods is demonstrated, matching simulations.

Introduction:
The ability to manipulate optical data with light instead of electronics is of strategic importance for future data networks. In many optical gates, light interacts with its surrounding medium that, in turn, may affect other optical signals passing through it. This has become the basis for a wide variety of switches, from soliton gates to waveguide devices, e.g. Refs. [1,2]. Unlike many of these devices, we present here a low-energy optical gate that can be both electrically or optically enabled at speeds important for telecommunications. Its optoelectronic nature potentially allows for a wide variety of novel applications, including simultaneous switching and data monitoring. The main new point of this work is the demonstration of the optically-controlled optical gate's (OCOG) operation with multiple successive pulses, showing burst logic rates at ~50GHz clock rate.[3,4] Moreover, our device is scalable to 2D arrays and integrable with CMOS by, e.g., solder bonding. An optical gate such as this might be useful, for example, in multiplexing and demultiplexing data streams or as a gated sampler in analog-to-digital conversion systems.

The gating mechanism of the OCOG is the non-linear absorption dependence due to photogenerated-carrier-induced electric field changes in this p-i-n-p-i-n structure. Device operation is based on the combination of rapid movement of photogenerated carriers in bulk AlGaAs, the coupled voltage dynamics between stacked diodes, and diffusive conduction[5] (the primary decay mechanism of the voltage build-up within the device). We show here for the first time both large-signal response from a dual-diode structure as well as device response with multiple pulses.

Theory:
This optically controlled optical gate is composed of two p-i-n diodes on top of a distributed Bragg reflector (DBR) mirror. The bottom (modulator) diode, which embodies multiple quantum wells (MQW) in its intrinsic region, has its absorption switched when an incident control pulse is absorbed in the top (control) diode.

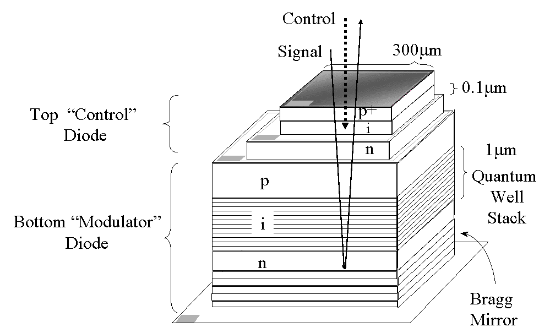

Fig. 1: Device schematic of a double diode structure with an ITO deposition over a thin top diode (100 nm intrinsic region) and a p-i(MQW)-n bottom diode.

The control diode, operated under reverse bias, is designed to be transparent to the signal (probe) pulse, but opaque to the control (pump) pulse, which is at a shorter wavelength. The modulator diode is initially only slightly reverse-biased so that the quantum wells are substantially transparent to the signal; the system is in its highly reflective state for the signal. When the control pulse hits the top diode, it is fully absorbed, creating electrons and holes primarily in the control diode's bulk intrinsic region. Because of the reverse bias, these photogenerated electrons and holes migrate to the n-region and p-regions, respectively. As the carriers vertically separate, they locally screen the bias-induced electric field, decreasing the reverse voltage across the top diode in the vicinity of the control pulse spot. As a consequence of the dual-diode structure (see below), the reverse bias voltage on the bottom diode is locally increased, thereby making the quantum wells more absorbing through quantum confined Stark effect (QCSE), and reducing the reflectivity of the signal. The voltage build-up time, and hence the "turn-on" time of the device, is determined by the transport times of carriers in the bulk material, ~1ps for the thin intrinsic region of the top diode. The "turn-off" time of the device is controlled by the local electrical relaxation of the voltage across the diodes through so-called diffusive conduction.

This dual diode structure can be modeled as multiple dielectric layers (intrinsic regions), each sandwiched between conducting layers (p- and n-regions). The highly conducting top-most and bottom-most layers of the entire device force the structure to keep the voltage across it effectively constant. Therefore, any local voltage *reduction* in the top diode leads to a corresponding local voltage *increase* in the bottom diode.

Since the voltage change is local compared to the lateral area of the device, the voltage build-up views the structure as a 2D transmission plane made from a mesh of resistances (p- and n-regions) and capacitances (across the intrinsic regions). Therefore, the voltage build-up diffuses away laterally through diffusive conduction. This decay mechanism, operating on a picosecond time scale, returns the device to its initial operating condition, turning "off'' the gate. The device repetition rate is not limited by the external RC time constants; rather, it is this much faster on-off cycle, occurring in picoseconds, that is the primary limitation to the device repetition rate. Note that the operation of the device can be disabled electrically by turning off the bias voltages, thus allowing electrical control of the optical switching.

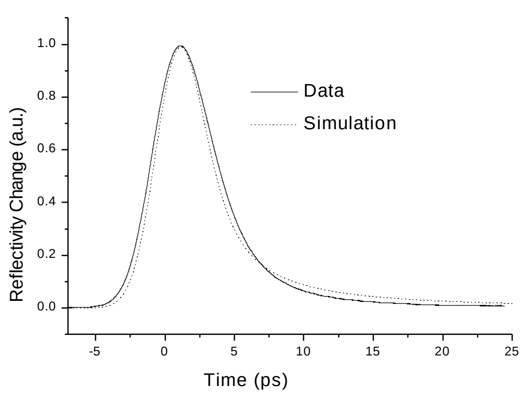

Fig. 2: Small signal response of the optical gate, with a 11.3 ps full width 10% maximum turn on-off time.

Design and Testing:

The device is a molecular beam epitaxy (MBE) grown AlGaAs structure. On the top of an n-doped GaAs substrate a DBR stack was placed consisting of 20 pairs of alternating AlAs and $Al_{0.3}Ga_{0.7}As$ layers and centered at 850 nm. An n-i-p diode was then grown with a 1 μm thick intrinsic region consisting of 60 pairs of 120 Å GaAs wells and 40 Å AlAs barriers. Above that another n-i-p diode was deposited, although here the intrinsic region was bulk material and thin, 0.1 μm. The topmost (p-doped) layer is very thin, just 50 nm including a GaAs capping layer. Except for the bottom diode's intrinsic region and the DBR mirror, all other layers are $Al_{0.3}Ga_{0.7}As$. To increase the conductivity of the top p-layer, 660 nm of indium-tin-oxide (ITO) was deposited and annealed (at 500^{o} C, for 5 minutes); this layer also acts as an anti-reflection coating. (The ITO we used was 75% absorbing instead of an expected 5-10%. We believe this was due to processing difficulties and not inherent to the device operation. Consequently, in this paper we discount the ITO absorption in reflectivity and power calculations.) Device processing produced square mesas 300μm wide on a side with wire-bonds to each of the four conducting layers of the double-diode structure.

A *Tsunami* Ti-Sapphire laser operating at 82 MHz was used to generate 2 ps pulses at 870 nm. A standard pump-probe set-up was used for testing with a BBO crystal (1 mm thick) used to upconvert the pump to 435 nm.

To test the device's response to multiple optical pulses, a stream of four control pulses was generated and focused on the device. Creating such a pulse stream was accomplished using a large beam splitter (5 cm x 5 cm) and four corner cubes, one on each side of the beam splitter. The original control pulse passed through the beam splitter and divided in half. Each of these two beams reflected from a corner cube back into the beam splitter and, consequently, split again. With careful alignment, the initial two beams overlapped when they again split. The result was four beams (two pairs of two) which, in turn, were retroreflected by two more corner cubes and overlapped once more in the beam splitter before splitting a third time. The final result was eight beams (two groups of four), half of which went to a beam-dump and the other half of which exited the beam splitter spatially overlapped. Each of these remaining beams had been retroreflected from a unique combination of two of the four corner cubes. As a result, by varying the individual corner cubes' distances from the beam splitter, it was possible to control each pulse's relative time delay with respect to the others. Because of the multiple splittings and reflections involved in creating the pulse stream, the final power in each pulse was limited to the small-signal regime (~1.3pJ/pulse).

Results:

With a 70 fJ switching energy, small-signal behavior of this device, showing an 11.3 ps turn on-off time, is depicted in Figure 2. Using expected or measured values for pulse width (2 ps), spot size (3.5 μm radius), layer thicknesses and resistivity, as Figure 2 demonstrates, there was very close agreement between theory and recorded data.

Large-signal device behavior (not simulated) is presented in Figure 3. The spot size radius was again 3.5 μm, while the switching energy was 1.5 pJ (39 fJ/μm^2). Excluding the parasitic absorption of the ITO (described above) and top p-layer, approximately a 2-to-1contrast ratio was achieved with a change in absolute reflectivity of about 30%. The optical gate opens and closes -- returns to 10% of maximum change -- within 19.6 ps.

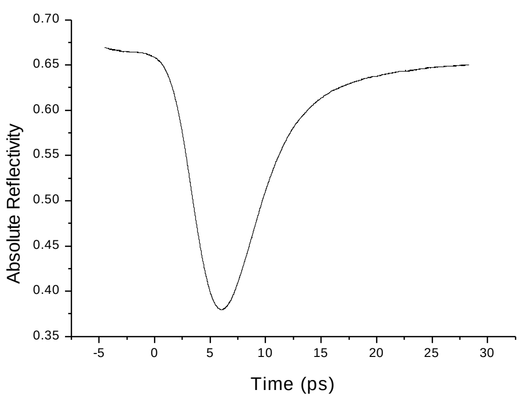

Fig. 3: Large-signal response of the optical gate with a 30% reflectivity change.

This slightly slower response compared to small signal behavior likely occurs because the carriers fully screen the reverse bias across the top diode before they reach the doped layers, slowing vertical carrier transport.

Figure 4 shows the device's response to four control pulses, each separated by 20 ps. Simulation results match well, with the discrepancy likely due to imperfect matching of the pulse energies in the pulse stream generator. The device's ability to recover in a short time is clearly evident. There is a slight increase in the base reflectivity level for the later pulses due to the build-up of previous pulses' decay. Simulations show that this build-up of base reflectivity (critical if the device is to be used as a modulator at these rates) levels off to a manageable level not far from what is already seen here.

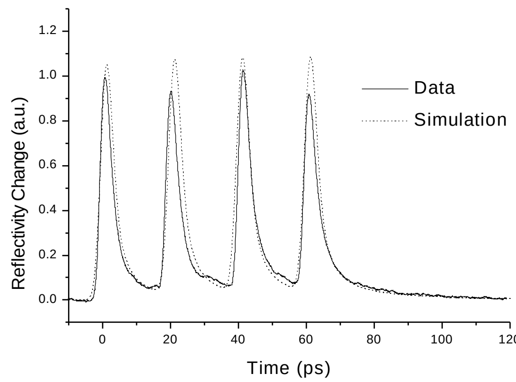

Fig. 4: Multiple-pulse, small-signal response of the optical gate with 20 ps pulse separation.

Conclusions:

We have demonstrated that a surface normal, optically controlled optical gate turns on and off within 20 picoseconds with a 30% reflectivity change, and that the device can operate with a 20 picosecond pulse repetition period. Future work may include improving processing techniques (particularly of the ITO), optimizing the modulator structure for larger contrast ratios, and fully integrating with a CMOS system via flip-chip bonding.

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