Optically-switched Dual-diode Electroabsorption Modulator

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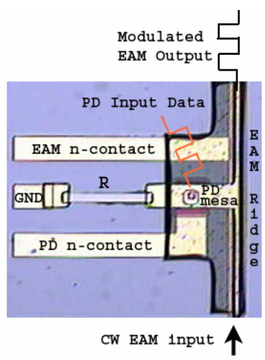
1. Introduction

Electroabsorption modulators (EAMs) are typically electrically driven to vary the electric field across the device and hence the optical transmission through it [1]. Waveguide EAMs are increasingly being used in optical networks since they can be monolithically integrated with continuous-wave (cw) edge-emitting laser diodes to create low-cost, high-speed optical transmitters. Recent work has also demonstrated optical control of the electrical field across an EAM opening up additional applications such as wavelength conversion [2-3], partial optical regeneration [4], and WDM to TDM conversion [5]. In fact, conventional optical-electrical-optical conversion can perform these tasks, but currently suffers from several disadvantages including high component and packaging costs, large space and power consumption, high complexity, a lack of scalability, and bit rate and format dependence [6]. To overcome some of these limitations, optically-switched EAMs have been proposed, but initial demonstrations have required large optical input powers (on the order of tens of millitwatts) to observe sufficient cross-absorption-modulation [7].

In this paper, we introduce a novel, waveguide, electroabsorption modulator diode that is monolithically integrated with a surface-normal illuminated photodetector (PD) requiring only milliwatt-level optical switching powers. Figure 1a shows a finished device illustrating the proposed integration. The integrated EAM waveguide and PD mesa diodes are interconnected such that an optical input data stream incident on the PD efficiently screens the electric field across both diodes. Through the quantum confined Stark effect [1], this change in the electric field is converted to a change in the optical transmission of the EAM. If another cw beam is coupled into the EAM, the optical information of the PD input will be transferred to the output beam of the EAM.



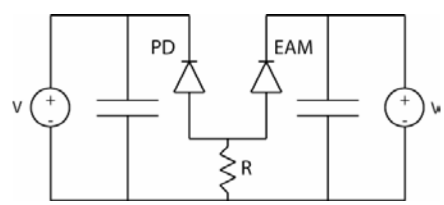


Figure 1: (a) Plan view of the integrated device, (b) Simplified circuit diagram of the device

Compared to planar waveguide approaches, the incorporation of the surface-normal PD in this dual-diode switch makes it possible to more easily scale this device into a two-dimensional matrix, for example, into a crossbar switch array. In principle, this architecture offers switching operation independent of the input beam wavelength and polarization unlike other optically switched waveguide EAMs. Furthermore, this device can efficiently convert a longer wavelength to a shorter wavelength and vice versa. The requirements for the realization of such a switch are to incorporate separate epitaxial layers for the PD and EAM, fabricate small geometry diodes, put them close together into a compact device, and interconnect them without introducing significant parasitics. In this work, we propose a monolithic integration scheme for our PD-EAM switch based on selective area regrowth (SAR). Here, we present the results of the SAR of the photodiodes, and demonstrate that the implemented integration meets the requirements of the fabrication of the optically switched, dual-diode EAM.

2. Device Concept and Design

Our group has previously demonstrated a class of EAMs integrated with PDs optically-switched at speeds up to 50 GHz using a switching energy of 1.5 pJ [8]. In these structures, the PD was grown on top of the EAM, and both diodes were used in a surface-normal configuration. In this architecture, the wavelength of the EAM input had to be longer than that of PD input, constraining the wavelength conversion. Moreover, these devices exhibited low extinction ratios due to the short active region length traversed by the EAM input beam. We have also implemented the same device concept with the use of a waveguide EAM that was optically-switched up to 2.5 GHz with increased extinction ratios up to 7dB, while requiring only milliwatt-level input beam powers [9]. However, this was a single-diode structure, and thus it did not have the design and operation flexibility of a dual diode structure.

The device we present here is based on a dual diode architecture, consisting of an EAM waveguide integrated with a surface normal PD mesa on the side, as pictured in Figure 1a. The diodes are interconnected to a local resistor on-chip. The overall circuit size is minimized to allow for high-speed lumped circuit operation requiring low optical switching powers. Figure 1b shows a simplified circuit schematic. The diodes are independently biased through a pair of by-pass capacitors. One (p-) side of each diode is attached to the ground through the on-chip resistor. When the input data stream is incident on the PD, the generated photocurrent creates a voltage drop across the common resistor, which in turn modulates the voltage across the EAM. If the optically induced voltage swing across the EAM, or alternatively extracted photocurrent from the PD to the resistor is large enough, the optical transmission properties of the EAM can be strongly modified. The capacitances of the EAM and PD are effectively connected in parallel. Any parasitic capacitance connected to the PD-EAM interconnect adds to the total capacitance of the switch increasing the required optical input power but such capacitance is minimized by the integration.

3. Device Integration

The realization of the proposed circuit requires intimate integration and high-speed interconnection of the EAM waveguide with the PD mesa. We have developed a two-step MOCVD growth process to match these integration requirements. The EAM epitaxial layers are grown first and etched into waveguide ridges separated by 500 μm. The PD epitaxial layers are subsequently selectively regrown on the wafer. Figure 2a shows a scanning electron micrograph of a typical regrown wafer. For our selective area regrowth, a SiN film patterned into stripes around the waveguides serves as a regrowth mask to encapsulate the waveguides and some surrounding area. The area adjacent to the waveguides covered by the regrowth mask is used to make electrical contact and to simplify PD mesa definition. In our process, the PD epitaxy is grown after the EAM epitaxy because the PD is composed primarily of binary and ternary materials leading to easier regrowth, and the regrowth mask stripes required to cover the EAM ridges mitigate growth enhancement.

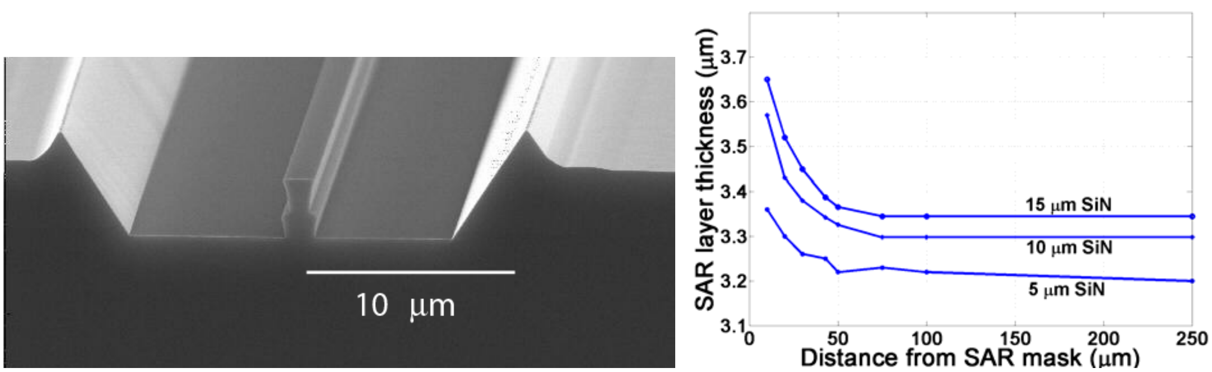


Figure 2: (a) SEM of selective area regrowth, (b) SAR layer thickness profile

We observe typical growth enhancement peaks along the (111)B plane next to the regrowth mask followed by a slow roll-off, with each epitaixal layer encapsulating lower epitaxial layers on the (111)B planes. Figure 2b plots the thickness of the regrown PD epitaxy as a function of the distance from the regrowth mask edge for different mask widths. The PD epitaxy exhibits a thickness variation in the first 50 um from the regrowth masks and then stabilizes to a thickness a few thousand Angstroms larger than the intended PD height. The growth enhancement places a constraint on the minimum spacing between the EAM and PD diodes. For the implementation of our switch, PD mesas should be placed at least 50 um away from the regrowth mask edges for the mask stripe widths of 15 um or less. To pattern the PD mesa, while properly clearing the (111)B planes near the regrowth mask edges, a carefully chosen series of selective wet and shallow dry etches are used. To passivate and electrically interconect the PD mesas and EAM waveguides, a multi-level planarization technique has been developed.

Figure 3a shows the individual I-V curves of a PD and an EAM integrated on the same chip. Typical characteristics are a breakdown voltage of –10.5 V and –17.4V (defined as voltage where leakage current is –1 μA), a leakage current density of $1.1x10^{-4}$ kA/cm^2 and $1x10^{-4}$ kA/cm^2 at the breakdown voltage for the PD and EAM, respectively. These results indicate the high quality of the PD epitaxy regrown next to the EAM and their successful passivation and integration. The maximum photocurrent that can be extracted from the regrown PDs before catastrophic failure is 2.5 mA, which corresponds to a field swing greater than 2V/um across the EAM for a switch designed to operate at a bit rate of 2.5 Gb/s. This optically induced electrical field swing is comparable to those used in conventional electrically driven EAMs. Figure 3b shows the simulated performance of the EAMs integrated with such regrown PDs using empirically measured electroabsorption spectra of the EAMs and photocurrent capabilities of the PDs. With an average PD input power of about 1.5 mW at 2.5 Gb/s, the EAM output beam is transmitted with an extinction ratio larger than 10 dB. The optically induced electric field swing can further be increased through scaling down the sizes of the PD and EAM. The extinction ratio of the EAM output can also be improved by optimizing the quantum well growth and design to achieve a lower background absorption and a larger absorption change per unit electric field swing.

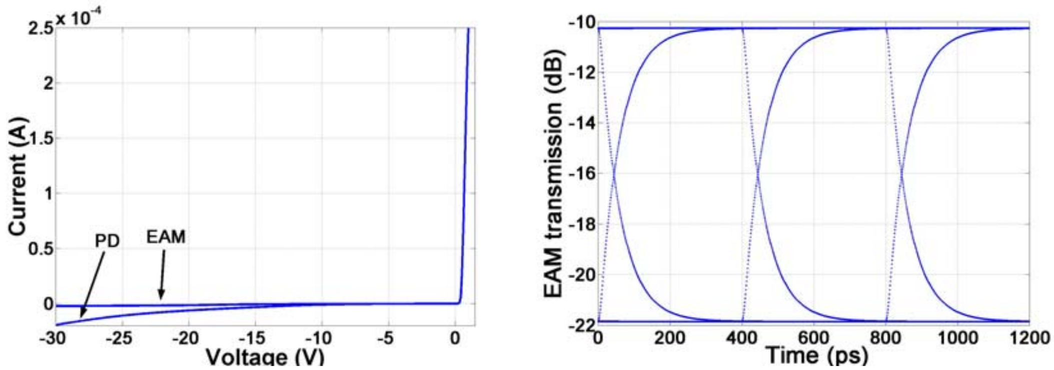


Figure 3: (a) IV curves of integrated PD and EAM, (b) Simulated device performance

4. Conclusion

We have introduced the monolithic integration of waveguide EAMs with surface normal PDs for the realization of a novel optically controlled optical switch. We have demonstrated a selective area regrowth technique that meets the integration requirements of the switch. To achieve intimate integration of the EAM with the PD, we have found that the minimum diode separation can be 50 μm for a regrowth mask width of 15 μm. We have developed device processing techniques that can accommodate the regrowth issues such as overall regrowth enhancement of the PD epitaxy across the wafer and the emergence of the (111)B plane near the SAR mask. We have demonstrated functional PD and EAM diodes integrated on the same chip and predict an electric field swing larger than 2 V/μm across PD-EAM corresponding to a switch performance of an extinction ratio greater than 10 dB with an incident PD input power of 1.5 mW at 2.5Gb/s for the C-band. Further scaling of the device dimensions and optimization of the electroabsorption properties of the quantum wells will allow for reduced PD input powers and increased optically-induced electric field swings resulting in the capability for high speed operation exceeding 10 Gb/s.

5. References

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