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Data Transmission at 1.3 μm Using Hybrid Integrated Silicon Interposer and GaInNAs/GaAs Electroabsorption Modulator

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Abstract *Transmission of NRZ data at 12.5 Gbit/s is demonstrated using a hybrid integrated silicon photonics optical interconnect. The interconnect comprises a dilute nitride quantum well electroabsorption modulator on GaAs substrate, which is optically coupled to large core Si waveguide.*

Introduction

Demand for bandwidth intensive data and video streaming services is increasing, calling for continuous development and deployment of new optical interconnect technology in data centres[1]. To this end, the use of large core Si waveguide technology, i.e. rib-waveguides[2], and active III–V optoelectronic devices has gained popularity for hybrid integration. The main advantages associated with using 3 μm or 12 μm thick silicon-on-insulator (SOI) waveguides are related to their insensitivity to polarization, dimensional variations, surface roughness, reduced nonlinearity, and the excellent mode match with I/O connectors and III–V active waveguides[3]. On the other hand, thick Si waveguides cannot be used to provide fast enough modulation in Si. Therefore, this platform requires the integration of either directly modulated lasers or electroabsorption modulators (EAMs). For example, this heterogeneous platform has been used recently to demonstrate a 400 Gbps transceiver based on the hybrid integration of directly modulated vertical-cavity surface emitting lasers and photodiode arrays operating at 1300 nm[4]. On the other hand, the deployment of active modulation with EAM has been largely limited to 1.5 μm window and InP technology.

Here we demonstrate an optical interconnect platform consisting of hybrid integrated thick Si waveguide technology and EAMs based on dilute nitride multiple quantum well (QW) materials on GaAs substrate, i.e. GaInNAs/GaAs. Dilute nitride QWs are known to provide excellent absorption properties at 1300 nm[5], thus potentially enabling the fabrication of ultra-compact EAMs with high modulation speeds. Moreover, these materials have an advantage over InGaAsP, or AlInGaAs alloys grown on InP due to very large conduction band offset, leading to high temperature performance[6] with potential for un-cooled operation. These features are very important in particular for increasing the integration density and mitigating the need for active cooling at high data rates. Furthermore, the GaInNAs/GaAs platform has recently been used to demonstrate monolithic integration of 1.3 μm laser diodes on Ge substrate, opening a very promising approach for full-scale monolithic integration with Si/SiGe technology[7]. Ultimately, from the large-scale fabrication point of view, GaAs technology is compatible with microelectronics fabrication and is also benefiting from the availability of larger substrates at lower cost (i.e. 6" for GaAs compared to 4" for InP).

Modulator structure and waveguide design

The heterostructure design employed modelling of the quantum confined Stark effect (QCSE) based on acceptable parameters for dilute nitride QWs. The modulator structure incorporates 8 QWs and is shown in Tab. 1.

Tab. 1: Description of the epitaxial layer structure.

Material	**Thickness** (cm^{-3})	**Doping** (cm^{-3})
p-GaAs	200	10^{19}
p-AlGaAs	1000	$4*10^{17}$ – $4*10^{18}$
GaAs	100	
GaAsN	10	
InGaAsN	7-10	× **8**
GaAsN	10	
n-AlGaAs	1000	$3*10^{17}$
n-GaAs	300	$4*10^{17}$

The band structure was approximated using a 1D Poisson model[8]. Results from simulations show that the valence band offset at the GaAs-QW interface is ΔE_v = 0.06 eV, while the conduction band offset is ΔE_c = 0.26 eV for the chosen InGaAsN alloy. The calculated high value of conduction band offset ratio of Q_c=0.81 is in-

line with more advanced theoretical calculations and more importantly agrees with reported values of conduction band offset ratio for similar InGaAsN alloys[9]. Moreover, the layers are arranged in a manner that minimizes the accumulation of photo-generated holes[10]. The structure was grown by RF plasma-assisted molecular beam epitaxy using an established optimization routine[11].

The EAMs were designed to be high speed and compatible with flip-chip bonding. To accommodate both requirements, isolated pedestal high-speed contacts were used[10]. For these contacts, the metal was deposited on the top of the semiconductor material, where a robust metal contact can be made. Then, the large area contact was isolated from the device by etching through the epitaxial layers into the undoped semiconductor wafer. The length of the EAMs needed only be 200 µm for an extinction ratio (ER) of 10 dB. However, this was too short for cleaving and handling. As a result, additional 200 µm sections were added to the EAMs, which would be operated to transparency using a small forward bias. These sections could also be operated as low gain optical amplifiers using a larger bias. A scanning electron microscopy image of the EAM bar is shown in Fig. 1.

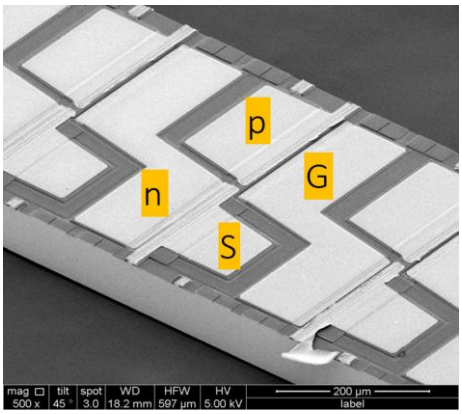

Fig. 1: Scanning electron microscope image of EAMs.

The EAM waveguide was designed to ensure alignment of its optical mode with the mode of the large core silicon waveguide after flip-chip bonding. Thus, the thickness of the EAM and the total metal thickness on the host silicon platform and on the EAM were chosen to minimise coupling losses; a schematic of alignment strategy is shown in Fig. 2. The silicon waveguide (WG) was 1.8 µm thick and was placed on top of a 3 µm oxide layer on the host silicon substrate. The cores of silicon waveguides were 6µm wide. Thus, the EAM WG width was also increased to 6 µm to minimise mode mismatch. These wide waveguides were chosen to ease the tolerances during the passive alignment. However, increasing the waveguide width in the EAMs resulted in a larger than intended capacitance, as described in the next section.

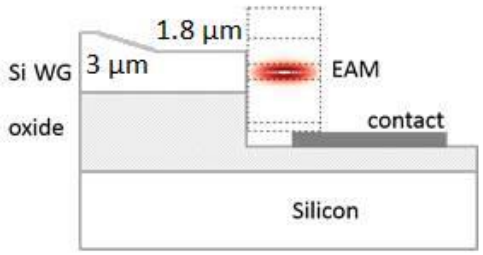

Fig. 2: Coupling between Si waveguide and EAMs.

Experimental Results

After cleaving the EAM bars, they were tested for DC and RF performance on a high-speed photonics probe station designed to accommodate bare bars. To confirm absorption based on the QCSE, the transmission through the EAM was measured as a function of input wavelength and reverse bias. The data shown in Fig. 3, reveals that the optical throughput can be substantially altered by applying a reverse bias. This is evidence for strong QCSE taking place inside the EAM. Data shows that the EAM can be operated at wavelengths around 1300 nm, where extinction ratio is 10 dB.

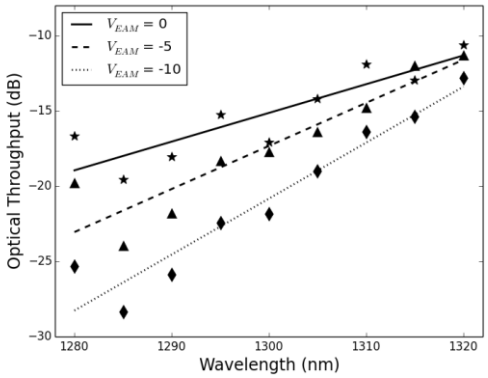

Fig. 3: Optical power transmitted through EAM under reverse bias.

The equivalent circuit of the EAMs was extracted from S_{11} reflection measurements made on the devices using a vector network analyser (VNA). The pedestal bond pads were found to have a capacitance of 38 fF, while the EAMs were found to have capacitances as high as 400 fF. A series of test bars were also characterised including EAMs with widths varying from 2 µm to 5 µm. The results shown in Fig. 4 demonstrate that the EAM capacitance can be significantly reduced by narrowing the waveguide

width, thus enabling much higher operating speeds.

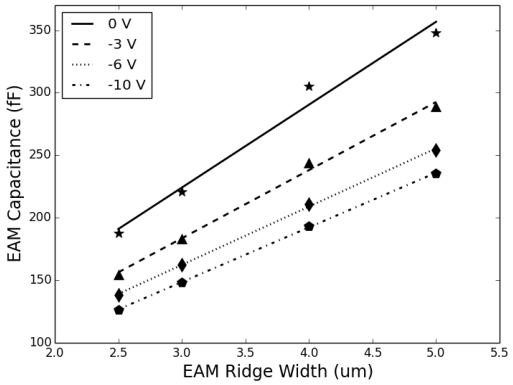

Fig. 4: EAM capacitance as a function of waveguide width for 200µm long EAMs.

After the EAMs were assembled on the silicon photonic modules, their large signal dynamic performance was characterised by performing a back-to-back measurement of transmitted NRZ data. Fig. 5 shows the eye diagrams from these transmission modules operating at 10 Gbps and 12.5 Gbps. At 10 Gbps the eye amplitude is 78.6 mV, and the signal to noise ratio (SNR) is 9.18 dB. At 12.5 Gbps the amplitude is 61.6 mV, and the SNR is 6.03 dB.

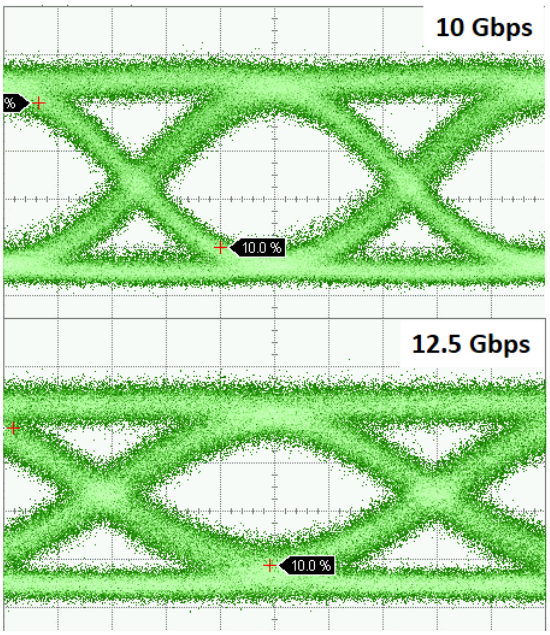

Fig. 5: 10 Gbps (top) and 12.5 Gbps (bottom) BtB eye diagrams showing operation of silicon photonics

Conclusions

Dilute nitride EAMs grown on GaAs substrates are demonstrated and integrated using passive alignment to silicon photonics transmission modules by flip-chip bonding. The devices were limited in speed due to the parasitic capacitance of the large waveguide width EAMs but still operated at speeds up to 12.5 Gbps. The bandwidth of the devices can be scaled-up to much higher data rates by narrowing the waveguides of the EAMs. This opens the way towards a high-speed un-cooled modulation platform for hybrid integrated optical interconnects using the versatile thick SOI technology and GaAs-based dilute nitride optoelectronics platform.

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