High-contrast quantum-confined Stark effect in Ge/SiGe quantum well stacks on Si with ultra-thin buffer layers

S. A. Srinivasan[1,2,a], C. Porret[1], E. Vissers[1], P. Geiregat[2,3], D. Van Thourhout[1,2], R. Loo[1], M. Pantouvaki[1], J. Van Campenhout[1]
[1)]Imec, Kapeldreef 75, Heverlee-3001, Belgium [2)]Photonics Research Group, Department of Information Technology, Ghent University – imec, Technologiepark-Zwijnaarde 16 iGent, Ghent-9052, Belgium [3)]Physics and Chemistry of Nanostructures, Ghent University, Ghent-9000, Belgium
[a)]ashwyn.srinivasan@imec.be

Abstract: Quantum-confined Stark effect with a record absorption contrast of 2.5 for 1V swing is demonstrated in Ge/GeSi quantum well stacks grown on Si using ultra-thin buffer layers, targeting future integration in a silicon photonics platform.

OCIS codes: (230.4205) Multiple quantum well (MQW) modulators; (200.4650) Optical interconnects

Previously, Ge(Si) based Franz-Keldysh effect (FKE) electro-absorption modulators (EAM) have been demonstrated in a silicon photonics platform, capable of transmitting data at >50 Gbps with ultra-low dynamic power consumption [1, 2]. However, these devices suffer from a relatively low absorption contrast ($\Delta\alpha/\alpha$) and the operation wavelength is limited to the 1550-1625 nm range. Quantum-confined Stark Effect (QCSE) based EAM using Ge quantum wells (QWs) have higher $\Delta\alpha/\alpha$ (greater than 2× as compared to Ge FKE EAM) and can be tuned to operate at 1310 nm. They typically require thick buffer layers for their growth on Si which increase the overall thickness of the device stack and make optical coupling with Si waveguides difficult [3,4]. In this work, we demonstrate Ge/SiGe QWs stacks grown on 300 mm Si (001) wafers using ultra-thin buffer layers (150 nm) without any significant degradation of the $\Delta\alpha/\alpha$ contrast. The demonstrated Ge/GeSi stacks have a total thickness of ~ 400 nm, enabling the future integration of QCSE EAMs with low drive voltage and low coupling loss in a 220 nm silicon photonics platform.

The device stacks under investigation in this work are based on an epitaxy strategy that results in a minimum strain build-up through the entire stack while using thin relaxed buffer layers, similar to the demonstration by Edwards et. al [4]. In these stacks, $Si_{0.11}Ge_{0.89}$ is used as strain-relaxed buffer layer, with 4× 14 nm-thick Ge QWs sandwiched between 18 nm-thick $Si_{0.19}Ge_{0.81}$ barrier layers. All the layers used in this work were grown in an ASM Intrepid™ reduced-pressure chemical vapour deposition production cluster. 150 and 300 nm buffer layers were grown on p-type B-implanted Si at 500°C using germane (GeH_4) and dichlorosilane (SiH_2Cl_2) as Ge and Si precursors. After growth, the buffers were subsequently annealed at 850°C in H_2 for 3 min to reduce the amount of threading dislocations and ensure a full relaxation, confirmed using X-ray Diffraction (XRD) and Reciprocal Space Mapping (RSM). Surface morphology inspections performed by Atomic Force Microscopy (AFM) revealed that the 150 nm buffer had a higher RMS roughness compared to the 300 nm case. Additionally, the defect density in the thinner buffer is expected to be higher than in the thicker buffer [5]. These degradations in the form of surface roughness and defectivity could introduce additional linewidth broadening to the measured absorption spectrum. The implanted region in the Si wafer formed the p-contact of the diode with active doping level of $\sim 3\times10^{18}$ cm^{-3}. Additionally, the 150 nm buffer was p-type in-situ doped using diborane (B_2H_6), yielding a doping level of 3×10^{18} cm^{-3}, so that the applied electric bias is effectively transferred up to the multi-QWs (MQW) region. QWs were grown at low temperature (< 400°C) using digermane (Ge_2H_6) and disilane (Si_2H_6) as precursors. The deposition of the MQWs was followed by the epitaxy of a 20 nm thick undoped $Si_{0.11}Ge_{0.89}$ barrier and a 90 nm thick n-type in-situ doped $Si_{0.11}Ge_{0.89}$ grown using arsine (AsH_3). The role of the undoped barrier layers is to avoid any dopant diffusion into the QWs region. The top layer, doped up to $\sim 1\times10^{19}$ cm^{-3}, formed the n-contact of the diode.

The QCSE-related shift in absorption was measured by monitoring the change in absorption related photocurrent in the diode as a function of applied electric bias. This measurement was facilitated by the fabrication of diodes formed by vertically dry etching circular mesas through the Ge/$Si_{0.19}Ge_{0.81}$ MQW stack down to the Si substrate. Ti/Pt/Au contacts were deposited with a circular opening to input light at the center of the device using electron beam evaporation and a subsequent lift-off process. The contacts were electrically isolated by SiO_2. Fig. 1 shows a microscope image of the fabricated device.

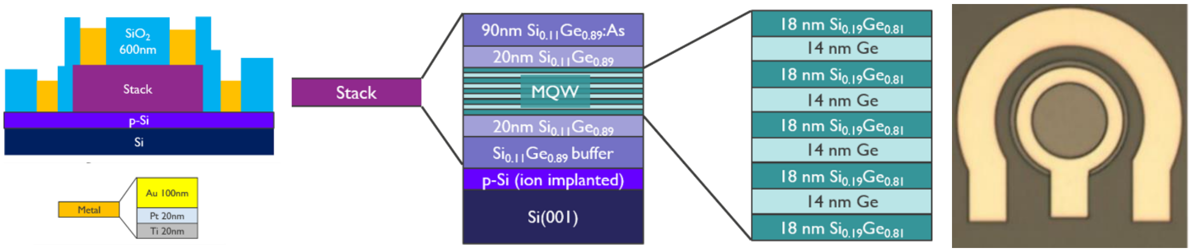
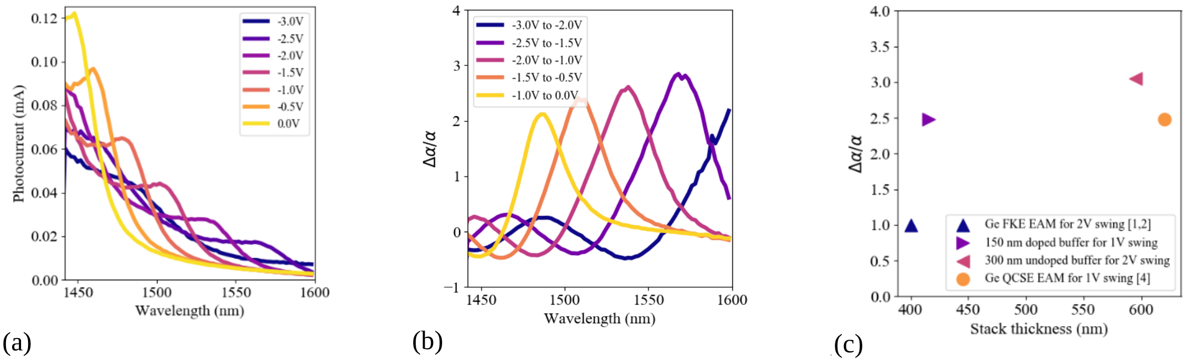


Fig 1. Cross-section schematics and top-view microscope image of a fabricated device with the MQW region grown on the $Si_{0.11}Ge_{0.89}$ *buffer.*

The MQW stacks, measured with a free space spectrometer, reveal a sharp absorption feature around 1425 nm at room temperature. To measure the photocurrent-mediated Stark effect, the devices were heated to 75°C to shift the absorption spectrum by 40 nm to the wavelength range supported by the tunable laser (1440 -1640 nm). The measured response for the MQW stack grown on the 150 nm buffer is shown in Fig. 2 (a). The photocurrent response was extracted by subtracting the dark current from the light current. As the reverse DC bias was increased in the diode, the electric field in the MQW region also increased resulting in a red shift in absorption spectrum due to the Stark effect. Absorption contrast ($\Delta\alpha/\alpha$, also known as Figure of Merit) for a voltage swing of 1 Vpp and variable DC bias was extracted from these photocurrent responses and is shown in Fig. 2. (b). It was found to vary from 2.2 to 3.0, depending on the operating wavelength, with an average value of 2.5. The absorption contrast from the 300 nm buffer stack, shown in Fig. 2 (c), was extracted for a voltage swing of 2 Vpp since the buffer layer was undoped. Therefore, the voltage applied over the diode did not efficiently translate to high electric fields. As a result, the E-field contrast for 2 Vpp (~ 46 kV/cm) from the MQW stack grown on the 300 nm undoped buffer is similar to the one obtained with 1 Vpp from the stack grown on the 150 nm doped buffer. Fig. 2 (c) summarizes the absorption contrast for an E-field of ~ 46 kV/cm, extracted from the Ge based EAMs presented in this work and in previous literature [1,2,4]. By reducing the buffer thickness from 300 nm to 150 nm, $\Delta\alpha/\alpha$ drops from 3 to 2.5 due to linewidth broadening introduced by the increased surface roughness and the higher defect density. Nevertheless, such measured $\Delta\alpha/\alpha$ is 2.5× larger than the Ge based FKE EAM. This demonstration based on a 150 nm thin buffer and comparable total stack thicknesses, is crucial for realizing a waveguide integrated QCSE EAM.



(a) (b) (c)

Fig. 2. a) Photocurrent spectra of the surface illuminated diode with MQW grown on a 150 nm-thick buffer. b) Absorption contrast ($\Delta\alpha/\alpha$*) for E-field contrast of ~ 46 kV/cm estimated from the photocurrent spectra. c) Comparing the measured* $\Delta\alpha/\alpha$ *for an E-field contrast of ~ 46 kV/cm from Ge EAMs in [1,2,4] to the devices in this work.*

To summarize, quantum-confined Stark effect with record absorption contrast of 2.5 for 1V swing is demonstrated in Ge/GeSi MQW grown on ultra-thin buffer layers. This contrast is greater than 2× as compared to Ge FKE EAM and can enable waveguide-integrated QCSE EAMs with low coupling loss in a 220 nm silicon photonics platform due to a total stack thickness limited to ~ 400 nm.

Acknowledgement. This work has been carried out as part of imec's industry-affiliation program on Optical I/O. Air Liquide Advanced materials is acknowledged for providing Ge_2H_6. Pieter Geiregat acknowledges the FWO Vlaanderen for a postdoctoral fellowship.

[1] M. Pantouvaki, et al. Journal of Lightwave Technology 35.4 (2017): 631-638.
[2] S. A. Srinivasan, et al. Optical Fiber Communications Conference and Exhibition *(OFC), 2016*. IEEE, 2016.
[3] Kai Zang, et al. Journal of Lightwave Technology 35.21 (2017): 4629-4633.
[4] E. H. Edwards, et al. Optics express 21.1 (2013): 867-876.
[5] Wang, G., et al. Applied Physics Letters 94.10 (2009): 102115.