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O-band quantum-confined Stark effect optical modulator from Ge/$Si_{0.15}Ge_{0.85}$ quantum wells by well thickness tuning

Papichaya Chaisakul,[1,a)] Jacopo Frigerio,[2] Delphine Marris-Morini,[1,b)] Vladyslav Vakarin,[1]
Daniel Chrastina,[2] Giovanni Isella,[2] and Laurent Vivien[1]
[1]*Institut d'Electronique Fondamentale, Univ. Paris-Sud, CNRS UMR 8622, Bât. 220, 91405 Orsay Cedex, France*
[2]*L-NESS, Dipartimento di Fisica del Politecnico di Milano, Polo di Como, Via Anzani 42, I-22100 Como, Italy*

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We report an O-band optical modulator from a Ge/$Si_{0.15}Ge_{0.85}$ multiple quantum well (MQW). Strong O-band optical modulation in devices commonly operating within E-band wavelength range can be achieved by simply decreasing the quantum well thickness. Both spectral photocurrent and optical transmission studies are performed to evaluate material characteristics and device performance from a surface-illuminated diode and a waveguide modulator, respectively. These results demonstrate the potential of using Ge/$Si_{0.15}Ge_{0.85}$ MQWs for the realization of future on-chip wavelength-division multiplexing systems with optical modulators operating at different wavelengths over a wide spectral range. © *2014 AIP Publishing LLC*.
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I. INTRODUCTION

Germanium (Ge) optoelectronic components could potentially play a key role in enabling future short range optical interconnects, meeting aggressive requirements in terms of power consumption, data density, and monolithic cost-effective integration with silicon.[1] Promising light detection, modulation, and emission properties of Ge on Si were demonstrated within the telecommunication wavelength using Ge direct-gap transition.[2–11] Particularly, quantum-confined Stark effect (QCSE) as strong as in III–V materials was demonstrated in Ge/$Si_{0.15}Ge_{0.85}$ multiple quantum wells (MQWs) coherently strained to a relaxed $Si_{0.1}Ge_{0.9}$ layer on a Si substrate.[12] The growth of thick Ge/SiGeGe MQWs was enabled by the strain compensation within the thick MQWs with respect to the relaxed p-type $Si_{0.1}Ge_{0.9}$ layer. Since then, the Ge/$Si_{0.15}Ge_{0.85}$ MQWs on $Si_{0.1}Ge_{0.9}$ relaxed layer were widely studied and efficient optical modulation was experimentally deduced from photocurrent data using surface-illuminated diodes within the E-band wavelength range of 1410–1460 nm.[12–14] High extinction ratio (ER) and low energy consumption waveguide and surface-illuminated optical modulators were experimentally verified via optical transmission measurements.[15–17] In order to obtain an optimal operating wavelength toward the O-band telecommunication wavelength range (1260 to 1360 nm), Ge/$Si_{0.4}Ge_{0.6}$ MQWs coherently strained to $Si_{0.18}Ge_{0.78}$ relaxed layer were theoretically proposed.[18,19] Experimental studies using vertical p-i-n diodes demonstrated significant absorption modulation from photocurrent spectra thanks to a larger compressive strain applied on the Ge quantum wells with respect to the underlining $Si_{0.22}Ge_{0.78}$ relaxed layer.[20,21] Using such methodology, an O-band waveguide optical modulator has been recently shown with promising modulation performance.[22]

In this paper, we experimentally demonstrate strong optical modulation within the O-band telecommunication wavelength by simply varying the quantum well thickness of the widely studied Ge/$Si_{0.15}Ge_{0.85}$ MQWs. Our approach significantly relaxes the practical fabrication complexity of Ge/SiGe MQW optical modulators operating at different wavelengths, which would be indispensable for future on-chip Si-based wavelength-division multiplexing (WDM) systems. In other words, the same Ge concentration could be employed to realize an optical modulator over a large wavelength range via varying only the QWs thickness, which could be achieved simultaneously across the wafer by using, for example, the local loading effect.[23] We employ both surface-illuminated and waveguide devices to thoroughly assess the optical modulation performance of the material systems via photocurrent and optical transmission measurements.

II. EPITAXY AND FABRICATION

Strained-compensated Ge/$Si_{0.15}Ge_{0.85}$ MQWs on $Si_{0.1}Ge_{0.9}$ layer were grown by low-energy plasma-enhanced chemical vapor deposition (LEPECVD).[24] This growth technique is a variant of the conventional chemical vapor deposition with additional use of a low energy plasma to control the deposition of silicon-germanium alloys. The plasma would strongly enhance the deposition efficiency comparing to conventional chemical vapor deposition, and the low energy of ions ($\sim$10 eV) avoids damage of the substrate and allows the deposition of crystalline materials. The sample was grown on a 100 mm p-Si (001) substrate with a resistivity of 1–10 Ω cm. Before heteroepitaxy, the native oxide was removed by dipping the substrate in aqueous hydrofluoric

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[a] Present address: Department of Materials Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan. Electronic addresses: chaisakul@microphotonics.t.u-tokyo.ac.jp and papichaya.chaisakul@u-psud.fr
[b] delphine.morini@u-psud.fr

acid solution (HF: H_2O 1:10) for 30 s. The first part of the structure consisted of a $Si_{1-y}Ge_y$ graded buffer, deposited at a rate of 5–10 nm/s, in which the Ge concentration was linearly raised from 0% to 80% with a grading rate of 7%/μm. The threading dislocation density in the top part of the graded buffer was $\sim 6 \times 10^6\,cm^{-2}$ as measured by chemical defect etching. The graded buffer was capped with a 2 μm thick $Si_{0.18}Ge_{0.82}$ layer, which would be used as an input waveguide for the experiments in waveguide configuration. Later, a 300-nm-thick relaxed $Si_{0.1}Ge_{0.9}$ layer was deposited and boron-doped ($\sim 5 \times 10^{18}\,cm^{-3}$). As confirmed by XRD measurements, the $Si_{0.1}Ge_{0.9}$ layer was relaxed; its thickness exceeded the critical thickness obtained for the 0.3% lattice mismatch with the $Si_{0.18}Ge_{0.82}$ layer (~40 nm according to Matthews and Blakeslee model[25]). The lattice mismatch is small enough that significant dislocations were not introduced during relaxation.[17] On the $Si_{0.1}Ge_{0.9}$ layer, a 35 nm $Si_{0.1}Ge_{0.9}$ spacer was grown. The MQWs themselves consist of 20 Ge QWs sandwiched between $Si_{0.15}Ge_{0.85}$ barriers grown at a rate of 1 nm/s. From the XRD analysis, we extracted a Ge QW width of ≈6.5 nm and a $Si_{0.15}Ge_{0.85}$ barrier thickness of ≈10 nm. Finally, a 35 nm $Si_{0.1}Ge_{0.9}$ spacer layer and a 100 nm $Si_{0.1}Ge_{0.9}$ phosphorous-doped n-type contact ($\sim 5 \times 10^{18}\,cm^{-3}$) were added. The whole MQW stack is coherent with respect to the 300-nm-thick $Si_{0.1}Ge_{0.9}$ layer (see Fig. 1(a)). To convincingly assess the optoelectronic modulation properties of the MQW stacks, both 50 μm diameter surface-illuminated and 100–μm-long, 4–μm-wide waveguide p-i-n diodes were fabricated. The mesa was patterned by standard ultraviolet (UV) lithography and dry etching. A SiO_2/Si_3N_4 passivation stack was deposited by plasma-enhanced chemical vapor deposition (PECVD). Using Si_3N_4 as a top insulation layer allowed a fast dry etching of Si_3N_4 by CF_4 gas stopping effectively on the SiO_2 layer, which was later removed by buffered HF wet etching, preventing any potential irradiation damage to the contact by dry etching. 100 nm of SiO_2 and 400 nm of Si_3N_4 were deposited at 300 °C using PECVD machine (STS system) at 13.56 MHz with SiH_4 and N_2O for SiO_2, as well as SiH_4 and NH_3 for Si_3N_4. The bottom and top contacts were defined by UV lithography, reactive ion etching, and wet etching of the passivation layer. A 1 μm thick Al layer was evaporated and lifted-off for both top and bottom contacts.

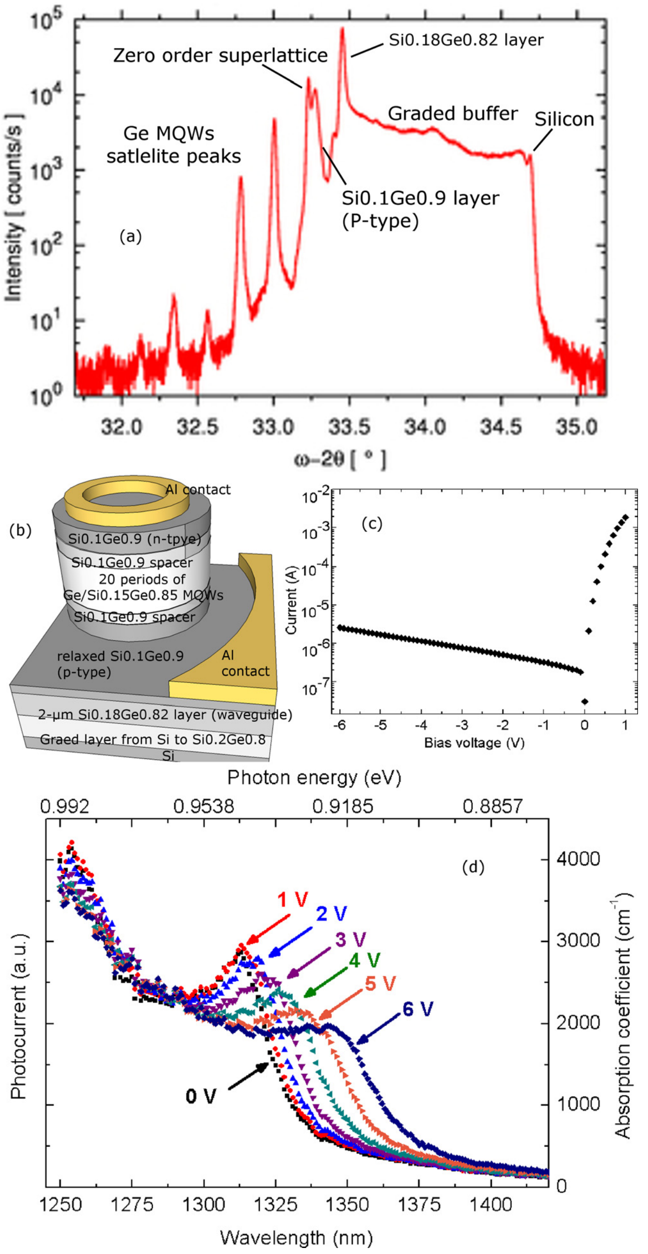

FIG. 1. (a) X-ray diffraction $\omega - 2\theta$ scan. (b) Schematic view of the Ge/SiGe MQW surfaced-illuminated diode. (c) I–V characteristic of the diode. (d) Room-temperature absorption spectra from the photocurrent measurement at different reverse bias voltages. The excitonic HH1-cΓ1 transition and strong QCSE were clearly observed within the O-band wavelength range (1260–1360 nm).

III. EXPERIMENT AND DISCUSSION

The optoelectronic properties of the QW stack were first measured from a 50 μm diameter surface-illuminated p-i-n diode. The schematic view of the fabricated device is shown in Fig. 1(b). The I–V characteristics of the Ge/SiGe MQW diode shown in Fig. 1(c) exhibited a good rectifying behavior with a dark current of 16 mA/cm^2 at -1 V reverse bias. The photocurrent measurements were performed at room temperature at various bias voltages with a spectral resolution of 1 nm using randomly polarized light from a tunable laser focused on the top surface of the diode. A chopper and lock-in amplifier were used to modulate the light intensity at 1 kHz and record the wavelength-dependent photocurrent spectra. Absorption coefficients in cm^{-1} were inferred from the diode responsivities assuming an ideal internal quantum efficiency of 100%,[12] and correcting for light reflection at the sample surface. The photocurrent spectra are shown in Fig. 1(d). From the experiments at 0 V bias, a clear exciton peak at room temperature was observed around 0.945 eV (~1312 nm), which can be attributed to the transition between the first valence band heavy hole level (HH1) and the first conduction band state at Γ (cΓ1). Additionally, the peak associated with the transition between the first valence band light hole level (LH1) and cΓ1 was also experimentally observed at a higher energy of around 0.989 eV (~1254 nm). By increasing the reverse bias, a strong QCSE was clearly observed from the $Ge/Si_{0.15}Ge_{0.85}$ quantum wells within the

O-band telecommunication wavelength. Two main characteristics of the QCSE were obtained: the Stark (red) shift of the absorption spectra and the reduction of the exciton-related absorption peak due to the reduction of the overlap between the electron and hole wavefunctions. In particular, from the photocurrent measurements, the Ge/$Si_{0.15}Ge_{0.85}$ MQWs sample showed potential for high extinction ratio and moderate absorption loss over 30-nm-wide spectral range from 1330 to 1360 nm.

The working spectra of the Ge/$Si_{0.15}Ge_{0.85}$ MQWs were successfully tuned to O-band wavelength from the previously demonstrated E-band wavelengths by simply changing the well width, owing to the fact that in quantum well systems the optical bandgap increases with decreasing QW width. Fig. 2(a) shows calculations performed within the effective mass approximation using the Nextnano software package.[26] The valence and conduction band offset have been calculated using the deformation potentials reported in Ref. 27 and the average valence band alignment experimentally determined in Ref. 28. As expected, the QW optical gap is seen to significantly increase while reducing the quantum well width. At around 6.5-nm-wide, an optical gap of 0.93 eV is obtained in good agreement with the experimentally observed HH1-cΓ1 exciton transition of around 0.94 eV. Fig. 2(b) reports the calculated optical bandgap energy and corresponding experimentally obtained data of Ge/$Si_{0.15}Ge_{0.85}$ MQWs at different quantum well thickness fabricated using the same process. The experimental values of Ge quantum wells thickness were obtained from the XRD analysis to be around 6.5, 9.5, 12, and 13 nm and also verified by cross-section high resolution scanning electron microscope (SEM) measurements. The corresponding HH1-cΓ1 excitonic transition wavelengths were obtained through photocurrent spectra at 0 V bias. Clearly, the experimental data of excitonic transition were well consistent with the calculated data at different quantum well thickness, confirming our experimental demonstrations of O-band operations from Ge/$Si_{0.15}Ge_{0.85}$ MQWs, by simply decreasing the well width down to around 6.5 nm. Additionally, one should note that in order to modulate efficiently at 1.31 μm the excitonic absorption should be further blue shifted to the 1265–1280 μm ($\sim$0.97 eV) as in the previous experimental[20,21] and theoretical[18,19] works using Ge/$Si_{0.4}Ge_{0.6}$ MQWs coherently strained to $Si_{0.18}Ge_{0.78}$ relaxed layer. From the calculation in Fig. 2(b), this could be obtained by decreasing the quantum well width to around 5.5–6 nm. However, this might lead to poor electron confinement as seen in Fig. 2(a) where the calculated confinement energy for electrons and HH is reported for different QW widths. Carefully noted, small discrepancy between the calculated results with early studies of Ge/SiGe might stem from the discrepancy between the reported nominal well thickness and the actual layer thickness, and/or the difference in material parameters used in calculations.

A 100-μm-long 4-μm-wide waveguide optical modulator was also fabricated to assess the optical modulation performance via optical spectral transmission measurements at different reverse bias voltages. The schematic view of the fabricated device is shown in Fig. 3(a). For the optical transmission measurements, light from a tunable laser (TUNICS, Yenista Optics) was butt-coupled into the optical tested devices using a lensed fibre. A polarizer was used between the light source and the device to selectively inject light with the electric field parallel to the Ge QW plane (TE polarization) according to the polarization dependence of the QCSE in Ge/SiGe MQWs.[29] The transmitted light from the tested device was coupled into a photodetector by an objective system. The spectra were swept simultaneously over the spectral range (All-Band Optical Component Tester MT9820A, Anritsu) with a resolution of less than 0.1 nm. The optical transmission spectra at different reverse bias voltages are reported in Fig. 3(b). The $Si_{0.18}Ge_{0.82}$ layer was employed as waveguide to inject light into and out of the 100-μm-long Ge/$Si_{0.15}Ge_{0.85}$ MQWs stack. The waveguide contribution to the spectra was subtracted by measuring the optical transmission of a near-by $Si_{0.18}Ge_{0.82}$ waveguide (See Fig. 3(a)). From Fig. 3(b), the measured transmission spectra clearly exhibited significant QCSE in the O-band wavelength range consistent with the results obtained from the above photocurrent measurements of a surfaced-illuminated diode. From Fig. 3(c), an ER of higher than 8 dB was achieved for over a 23-nm-wide spectral range, between 1327 and 1340 nm for a reverse bias of 5 V, and between 1332 and 1350 nm for a reverse bias of 6 V. With respect to the reference signal, we could see that the waveguide modulator has moderate insertion loss of around 5 dB at wavelengths longer than 1345 nm; however, the optical loss is seen to increase up to around 10 dB at 1327 nm. This means that, if operated 23 meV below the excitonic resonance, the studied 100-μm-long modulator can operate at 8 dB ER with 5 dB loss thus approaching the 5 dB ER with 3 dB loss (or FOM > 1.6) required for short-range applications.[19] We projected that

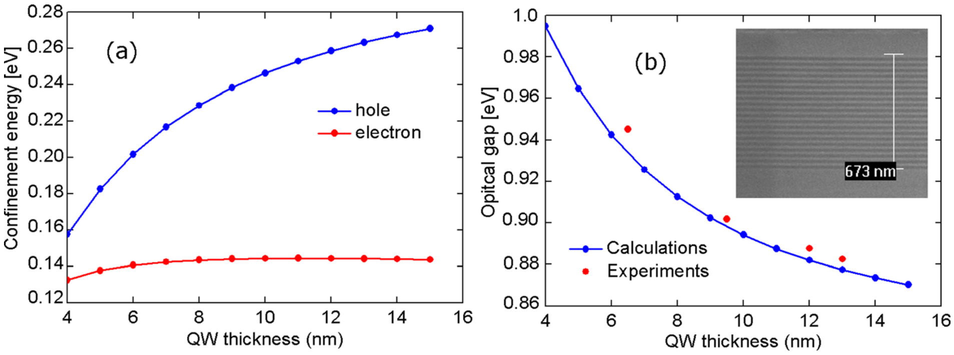

FIG. 2. (a) Calculated confinement energy of Ge/$Si_{0.15}Ge_{0.85}$ as function of quantum well width. (b) Calculated and experimentally obtained optical band gap transition energy of Ge/$Si_{0.15}Ge_{0.85}$ as function of quantum well width. In the inset, SEM image of 20 QWs with Ge well thickness of ≈13 nm.

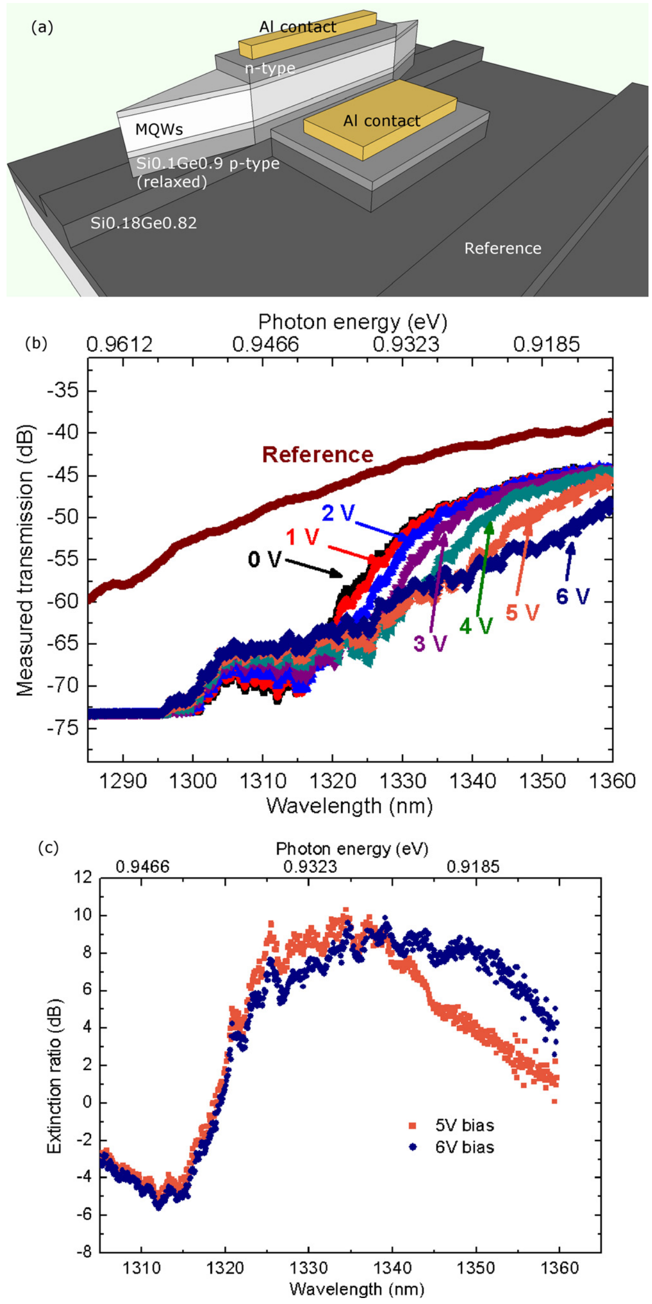

FIG. 3. (a) Schematic view of the Ge/SiGe MQW 100-μm-long waveguide diode. (b) Room-temperature absorption spectra from the transmission measurement at different reverse bias voltages. Strong optical modulation within the O-band wavelength range is confirmed. (c) Extinction ratio of the waveguide modulator between 0 and 5, 6 V.

apart from the traditional Ge indirect-gap absorption loss,[30] absorption from $Si_{0.1}Ge_{0.9}$ relaxed layers played an important role in overall loss obtained via optical transmission measurements of the studied O-band waveguide optical modulator. The latter loss contribution could not be sufficiently assessed via photocurrent measurements giving information related mainly to the quantum well band gap absorption.

IV. CONCLUSIONS

In conclusion, we experimentally demonstrated strong optical modulation within the O-band telecommunication wavelength from the widely studied $Ge/Si_{0.15}Ge_{0.85}$ MQWs by simply varying the quantum well thickness. The approach could significantly relax the practical fabrication complexity of Ge/SiGe MQW optical modulators operating at different wavelengths on the same wafer for future on-chip WDM. The photocurrent and transmission studies indicated that the material systems could reach good ER and sufficiently low loss operating 23 meV below the excitonic resonance.

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