Research article

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Asymmetric Ge/SiGe coupled quantum well modulators

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Abstract: We design and demonstrate an asymmetric Ge/SiGe coupled quantum well (CQW) waveguide modulator for both intensity and phase modulation with a low bias voltage in silicon photonic integration. The asymmetric CQWs consisting of two quantum wells with different widths are employed as the active region to enhance the electro-optical characteristics of the device by controlling the coupling of the wave functions. The fabricated device can realize 5 dB extinction ratio at 1446 nm and 1.4×10^{-3} electrorefractive index variation at 1530 nm with the associated modulation efficiency $V_{\pi}L_{\pi}$ of 0.055 V cm under 1 V reverse bias. The 3 dB bandwidth for high frequency response is 27 GHz under 1 V bias and the energy consumption per bit is less than 100 fJ/bit. The proposed device offers a pathway towards a low voltage, low energy consumption, high speed and compact modulator for silicon photonic integrated devices, as well as opens possibilities for achieving advanced modulation format in a more compact and simple frame.

Keywords: asymmetric coupled quantum well; Ge/SiGe quantum well; silicon photonic integration; waveguide modulator.

1 Introduction

With the rapid development of optical communication and interconnection, the photonic integrated circuits (PICs)

play a crucial role in the information industry. The silicon photonic integration is regarded as an excellent platform for the next generation on-chip data transfer owing to the mature complementary metal oxide semiconductor (CMOS) technology. Compared with the complex hybrid integration, the monolithic silicon photonic is CMOS compatible and can be manufactured in large volume at low cost. Recently, group IV materials have drawn great attention and Ge-based photonics has been regarded as one of the most promising scheme to achieve monolithic integration of all active optical devices [1–3]. Despite of being an indirect bandgap semiconductor, the indirect band of Ge can be converted into direct band structure through introducing strain [4, 5] and Sn alloying [6, 7]. Besides, the abrupt absorption variation related to the direct bandgap can be realized by Ge quantum wells [8], even though the Ge quantum wells possess both direct and indirect bandgap. The direct bandgap optical properties of Ge have been intensively investigated and much impressive progress has been made for light source [9, 10], optical modulators [11, 12] and photodetectors [13, 14].

For Ge-based modulators, the Ge/SiGe multiple quantum well electroabsorption modulators based on quantum confinement Stark effect (QCSE) have been demonstrated to implement small footprint and low energy dissipation [15, 16], but the applied bias voltage is still a little high to obtain a high extinction ratio. On the other hand, few efforts have been made to explore the refractive index variation in the Ge/SiGe quantum wells owing to the change of the absorption spectrum as described by the Kramers-Kronig relation [17]. A preliminary demonstration of the electrorefractive index variation in Ge/SiGe multiple quantum wells [18] has been reported with an effective refractive index variation of 1.3×10^{-3} but the associated bias voltage is as high as 8 V, which limits its practical applications. However, the electro-optical characteristics can be further improved by coupled quantum wells structures and the CQWs structure has been widely investigated in III–V group material for various applications [19–21]. It has been theoretically and experimentally demonstrated that the symmetric Ge/SiGe coupled quantum wells can strongly enhance the electrorefractive index variation

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compared with the common quantum wells [22, 23]. An excellent result of a refractive index variation up to 2.3×10^{-3} under a reverse bias of 1.5 V was reported for the symmetric Ge/SiGe CQWs structure with a corresponding modulation efficiency $V_{\pi}L_{\pi}$ of 0.046 V cm.

In this work, we design and demonstrate an asymmetric Ge/SiGe coupled quantum well modulator for both intensity and phase modulation with a low bias voltage. By adapting different quantum well thicknesses, we can tailor the electro-optical properties of the device by controlling the coupling between the wave functions through the inner thin barrier. The wave function and electroabsorption spectrum are calculated by an eight band kp model [24]. Under 2 V reverse bias, the device can achieve 7.8 dB extinction ratio and 3.2×10^{-3} refraction index variation with the $V_{\pi}L_{\pi}$ of 0.024 V cm. The proposed device paves the way to realizing a compact, low voltage, low energy consumption and high speed modulator in silicon photonic integration for both intensity and phase modulation.

2 Design and fabrication

The structure of the proposed Ge/SiGe coupled quantum wells is shown in Figure 1. The CQWs are grown on a p-type (001)-oriented Si substrate by reduced-pressure chemical vapor deposition (RPCVD). To decrease the dislocations and surface roughness due to the lattice mismatch between silicon and germanium, a 400 nm thick boron-doped ($1 \times 10^{19} \text{ cm}^{-3}$) $\text{Ge}_{0.85}\text{Si}_{0.15}$ layer is first deposited on the substrate and an in-situ annealing process at temperature of 800 °C is then performed [25]. This process results in about 0.19% biaxial tensile stress [26, 27] because the buffer layer is not completely relaxed. The Ge/SiGe CQWs region consists of eight CQWs: $8 \times [6 \text{ nm Ge QW} + 2 \text{ nm Si}_{0.17}\text{Ge}_{0.83} \text{ inner barrier} + 12 \text{ nm Ge QW} + 24 \text{ nm Si}_{0.15}\text{Ge}_{0.85} \text{ outer barrier}]$, which is sandwiched between a pair of 50 nm thick intrinsic $\text{Si}_{0.15}\text{Ge}_{0.85}$ spacer layers to prevent the charge carrier diffusion during epitaxy. The whole structure is capped by a 200 nm thick phosphorus-doped $\text{Ge}_{0.85}\text{Si}_{0.15}$ layer with a doping level of $5 \times 10^{18} \text{ cm}^{-3}$. The threading dislocation density is below $2 \times 10^7 \text{ cm}^{-2}$ according to the etching pit microscope test. The 50 nm thick spacer layer is enough to ensure a very low background doping in the quantum well region. Figure 2 illustrates the TEM image of the Ge/SiGe CQWs and X-ray diffraction (XRD) scan along [001] direction. The interface between quantum wells and barriers is clearly visible, confirming a good quality of the superlattice. The Ω -2 θ scan curve contains several higher-order satellite peaks overlapped by the $\text{Si}_{0.15}\text{Ge}_{0.85}$ buffer peak, which is in good agreement with

the simulation result. To further evaluate the crystal quality of the samples, we add measurements for the XRD scan along the [224] direction (see Supplementary Material). It is noted that the peak positions of the measured XRD curve are not completely accordant with the simulation results owing to the residual tensile strain in the $\text{Si}_{0.15}\text{Ge}_{0.85}$ buffer layer after annealing process.

Figure 3(a) depicts the whole device structure and the fundamental mode of the SiGe rib waveguide. The SiGe waveguide is 2 μm in width and the rib height is 660 nm. The total waveguide length is 760 μm , including three sections, specifically of one 400 μm long center waveguide and two 180 μm long tapers with a linearly increasing width at both ends. The tapers are designed to couple light from or to focusing lensed fibers and the width of the butt coupling end is 8 μm . Since the SiGe buffer layer and cap layer are both heavily doped, the conductivity of the buffer and cap layers is strong enough to ensure the applied voltage uniformity along the waveguide and the modulation occurring both in the central part with the metallic contacts and in the tapers. The electrical field distribution of the fundamental mode shown in Figure 3(b) is obtained by the finite difference time domain (FDTD) commercial software and the optical overlap factor of the active CQWs region is 0.49. Even though the refractive index difference between the Si substrate and the SiGe waveguide is small, the optical field is well confined in the waveguide core.

Figure 4 shows the fabrication process of the modulator. The device is patterned by the electron beam lithography (EBL) to guarantee the high accuracy. Then the waveguide is etched by an inductively coupled plasma (ICP) etcher. The etch depth is 660 nm and the etching process stops at the p-type SiGe buffer layer. Next, the

Figure 1: (a) Epitaxy design of the CQWs structure. (b) Schematic of the asymmetric CQW.

Figure 2: (a) TEM image of the Ge/SiGe CQWs. (b) X-ray diffraction scan along [001] direction.

SiO₂/Si₃N₄ passivation layer is grown by the plasma-enhanced chemical vapor deposition. Then, the contact windows are defined, etched and followed by the metal contact lithography, evaporation and lift-off. Finally, the deep etch process is performed to achieve the butt coupling facet and the wafer is diced along the etch trench. The low power ultrasonic cleaning is utilized to remove impurities from the chip surface during the fabrication. Figure 5(a) displays the metalloscope image of the fabricated device

Figure 3: (a) Schematic of the device. (b) The field distribution of the fundamental mode in the device waveguide.

and the butt coupling facet is shown in Figure 5(b). To realize a higher coupling efficiency, the deep etching facet is a little slant to decrease the Fresnel reflection.

3 Theory and simulation

Figure 6 illustrates the calculated wave functions at the Γ point of the Ge/SiGe asymmetric CQWs for $e1$, $e2$, HH1, HH2 and LH1 energy states under different electric fields. Since the asymmetrical characteristic of the quantum well width, the $e1$ energy state and the HH1 energy state are obviously located in the wide quantum well when no electrical field is applied, which is much different from the case in symmetric CQWs and normal quantum wells. Due to the asymmetrical distribution of the electron and hole energy states, the original selected rules in standard uncoupled quantum wells are broken without the requirement of applied electrical fields and the optical transitions: HH1- $e2$, LH1- $e2$ and HH2- $e1$ are no longer forbidden. With the increasing of the applied electrical fields, the $e1$ energy state moves towards the narrow quantum well while the HH1 energy state moves to the wide quantum well further. Since the inner barrier is narrow, the wave function of the CQWs can change a lot under a relative lower applied fields

Figure 4: The schematic diagram of the fabrication process.

(a) Chip washing, (b) metal marks fabrication, (c) waveguide patterning and etching, (d) deposition of passivation layer, (e) contact windows patterning and etching, (f) metal contact patterning and evaporation, (g) lithography and deep etching and (h) chip dicing.

compared with the uncoupled quantum wells. The more remarkable movement of the wave functions in CQWs also leads to a more significant variation in spatial overlap factor in wave functions.

Figure 7(a) illustrates the simulated direct absorption spectrum of the Ge/SiGe asymmetrical CQWs under different applied fields. With the increment of the applied fields, the absorption band edge generates a prominent red shift owing to the reduction of the exciton binding energy of the HH1-e1 optical transition. The exciton absorption peaks are originated from the interband transitions between the diverse electron and hole energy states. In comparison with the uncoupled quantum wells (see Supplementary Material), the red shift is more noteworthy for the asymmetrical CQWs, which can realize a shift of about 28 nm under the applied electrical field of 50 kV/cm. The multiple interband transitions and the outstanding red shift result in a large electrorefractive index variation. According to the Kramers-Kronig relation [28], the refractive index variation can be expressed as:

$$\Delta n(\nu) = \frac{c}{\pi} \int \frac{\Delta \alpha(\nu')}{\nu'^2 - \nu^2} d\nu' \quad (1)$$

where ν is the frequency and $\Delta \alpha$ is the direct absorption variation caused by the applied fields. Figure 7(b) indicates the calculated electrorefractive index variation of the asymmetric Ge/SiGe CQWs as a function of the electrical field for different wavelengths. When the applied field is 40 kV/cm, the variation has a local maximum

about 0.009 for the wavelength of 1450 nm, which is much larger than that of the uncoupled quantum wells. The high electrorefractive index variation implies promising prospects for phase modulation. The electrorefraction usually works at longer wavelength than the electroabsorption for the Ge/SiGe coupled quantum wells, and the two effects are complementary thus can extend the operating wavelength range.

4 Measurements and discussion

4.1 Intensity modulation

We use a pair of single mode focusing lensed fibers to couple light into and from the Ge/SiGe waveguide. The light from a tunable laser is first injected to a polarization controller to obtain a transverse electric field (TE) input. The output light emerging from the waveguide is detected by an optical power meter. To insure the majority of the optical power is coupled into the waveguide instead of the Si substrate, we employ a set of precision optical fiber regulating frame to adjust the fiber position until the output optical power is maximal. The reverse bias voltage is applied to the contact electrode by a digital source meter. To avoid the movement of the sample chip, the electrode probe is pressed against the device before adjusting the coupling fiber. To prevent the disturbance from the manual operations, all the instruments are controlled through the

Figure 5: (a) Metalloscope image of the fabricated device. (b) SEM image of the butt coupling facet.

GPIB interface and the measurement data is recorded by a host computer.

Figure 8(a) shows the measured optical power as a function of wavelength under different bias voltages. The butt coupling loss for single end is about 5.4 dB and the overall waveguide transmission loss is less than 1.8 dB for the wavelength above 1445 nm. The insertion loss mainly contains the free-carrier-induced absorption loss, the optical propagation loss and the optical spot size converting loss. The corresponding electric fields are 27 kV/cm and 54 kV/cm for 1 and 2 V bias respectively and the measurements show good agreement with the simulated direct absorption spectra in Figure 7(a). When there is no applied

Figure 6: Simulated wave functions at the Γ point of the Ge/SiGe CQWs under the electric field of: 0, 10, 20, 30, 40 and 50 kV/cm.

electrical field, the detected optical power curve is almost flat from 1445 to 1485 nm because the current absorption edge is at about 1430 nm. In this case, the direct absorption from the CQWs is weak and the indirect absorption [29] is dominant. With the increase of the reverse bias voltage, the absorption edge generates a notable red shift caused by the QCSE effect. The minimal optical power points under 1 and 2 V reverse bias, which are corresponding to the absorption peaks, are at about 1446 and 1457 nm respectively. The excitonic peaks at 1 and 2 V are broader than the simulations because there still exists indirect absorption of Ge except for the direct absorption from the QCSE. Besides, it should be noted that a part of optical field is out of the quantum well region, which means some optical power transmits through the SiGe buffer and cap layers instead of the quantum well layers. These factors make the measured excitonic peaks broader than the simulations. Figure 8(b) illustrates the extinction ratio of the device for 0/1, 0/2 and 1/2 V bias operations. Under the 0/1 V operation, the maximal extinction ratio is about 5 dB at 1446 nm, which is far higher than that of the standard uncoupled quantum wells with such a low applied bias voltage. Under the 1/2 V operation, the maximal extinction ratio is about 5.7 dB at

Figure 7: (a) Direct absorption spectrum of the CQWs under different electric fields. (b) Electrorefractive index variation of the CQWs as a function of the electric field for different wavelengths.

1465 nm and the extinction ratio is over 4 dB in the wavelength range between 1453 and 1473 nm. Under the 0/2 V operation, the maximal extinction ratio is about 7.8 dB at 1457 nm and the wavelength range of extinction ratio above 4 dB is more than 32 nm. It should point out that the measuring wavelength range is limited by our tunable laser whose shortest wavelength is about 1442 nm.

4.2 Phase modulation

We use an EDFA as a broadband optical source to replace the tunable laser mentioned above and the output light coupled from the device waveguide is fed to an optical spectrum analyzer. To acquire more remarkable results, we

Figure 8: (a) Optical power spectrum under different bias voltages. (b) Extinction ratio of the device for different bias voltage operations.

chose a shorter waveguide with the length of 200 μm and two tapers with the length of 80 μm to observe the shift of Fabry–Perot (FP) interference fringes under different reverse biases, which implies the corresponding variation of the electrorefractive index.

Figure 9(a) shows the FP interference filtering spectrum of the device waveguide around 1530 nm under 0, 1 and 2 V reverse bias. The baseline for each curve has been shifted to separate from each other for better highlighting the interference peaks. The spectral peak shift $\Delta\lambda$ is related to the effective refractive index variation, which is given by

$$\Delta n_{\text{eff}}(\lambda) = \frac{\Delta\lambda}{\lambda} n_g(\lambda) \quad (2)$$

where n_g is the group index. The group index n_g can be experimentally deduced from the longitudinal mode spacing $\Delta\lambda_m$ by

$$n_g(\lambda_m) = \frac{\lambda_m^2}{2L\Delta\lambda_m} \quad (3)$$

where L is the total 360 μm device length of the waveguide and two tapers. It can be deduced that the electrorefractive index variation is respectively 1.4×10^{-3} and 3.2×10^{-3} under 1 and 2 V reverse bias at the wavelength of 1530 nm, as shown in Figure 9(b). The measurements are close to the calculated electrorefractive index variation in Figure 7(b). The corresponding product of the half wave voltage and the length of phase shift region, namely the $V_{\pi}L_{\pi}$, is respectively 0.055 and 0.024 V cm, which is an order of magnitude less than that of the common quantum wells [18, 30] and has strong competitive advantages over other silicon based phase modulators [31]. It should be mentioned that the absorption edge is substantially smaller than 1530 nm and a more significant electrorefractive index variation and a lower $V_{\pi}L_{\pi}$ product are expected within the range of short wavelength band (S band) in optical communication.

4.3 High frequency response

A 40 GHz vector network analyzer (VNA) is used to evaluate the high frequency response of the device. The microwave signal generated from the port 1 of the VNA and a reverse direct current bias are applied to the contact electrode of the device through a bias Tee and a GSG high frequency probe. The laser light at 1460 nm is butt coupled to the device and the output light is launched into a high frequency photodetector. The photo current signal of the photodetector is launched into the port 2 of the VNA. Before the measurement, we carry out the original calibration test for the whole system using a calibration substrate. The frequency response of the fabricated modulator is described as $Rf(M) = Rf(M + PD)/Rf(PD)$. The whole system response $Rf(M + PD)$ is directly measured and the photodetector response $Rf(PD)$ is obtained from the user manual of the product. The device used for the high speed measurement is the same as the one of the intensity modulation measurement.

Figure 10 indicates the high frequency response of the fabricated modulator under different reverse bias voltages. The 3 dB bandwidth of the device is about 24, 27 and 32 GHz respectively for 0, 1 and 2 V reverse bias, which is higher than the other reported Ge/SiGe quantum wells modulators. The response bandwidth is limited by the device

Figure 9: (a) FP interference filtering spectrum of the device waveguide under different reverse biases. (The baseline for each curve has been shifted to separate from each other). (b) Electrorefractive index variation of the device as a function of wavelength under different reverse biases.

junction capacitance which is estimated as 249 fF according to our simulation. The high frequency performance could be further enhanced by optimizing the dimension of the device and the size of the electrode. For the energy consumption, the device energy per bit is calculated by $C/4 (V_{\text{off}}^2 - V_{\text{on}}^2)$ in which C is the junction capacitance and V_{off} and V_{on} are the reverse bias voltages for the “off” and “on” states. According to the above formula, the energy dissipation per bit is calculated to be 62.25 and 249 fJ/bit respectively under the voltage swing of 0/1 and 0/2 V operations. Here we neglect the dark current that is quite low since the device operates at the reverse bias (see Supplementary Material).

Figure 10: Normalized high frequency response of the fabricated device.

5 Conclusion

In summary, we propose and demonstrate an asymmetric Ge/SiGe coupled quantum wells modulator for both intensity and phase modulation in silicon-based waveguide configuration with a low bias voltage. A novel asymmetric Ge/SiGe CQW structure with different quantum well widths is developed as the active region. The fabricated device can achieve 5 dB extinction ratio at 1446 nm and 7.8 dB extinction ratio at 1457 nm under 1 and 2 V reverse bias respectively. For phase modulation, the designed device can achieve 1.4×10^{-3} and 3.2×10^{-3} electrorefractive index variation at 1530 nm under 1 and 2 V reverse bias respectively. The corresponding $V_{\pi}L_{\pi}$ is respectively 0.055 and 0.024 V cm, which is significantly smaller than other silicon based phase modulators. The 3 dB bandwidth is 24, 27 and 32 GHz respectively under 0, 1 and 2 V reverse bias. The modulation performance can be further improved by optimizing the design of Ge/SiGe CQWs. For the electro-absorption modulation, we can increase the number of the CQWs and optimize the thickness of the buffer and cap layers to obtain a larger optical overlap factor of the active region. For the electrorefraction modulation, it would be even better than the Ge component percentage of inner barriers is higher than the out barriers. The higher Ge component percentage means lower barrier height of the inner barriers, which can further reduce the bias voltage for the same absorption edge shift. Besides, the thickness of the inner barriers could be further decreased to enhance

the coupling between the two quantum wells. The proposed modulator provides a competitive candidate for low voltage, low power consumption, high speed and compact modulators in silicon photonic integration and it also hold promise for realizing advanced modulation format in a more compact and simple system.

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