Mid-infrared Group-IV Optical Modulators on Silicon

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***Abstract*—We present a design of $Ge_{1-x}Sn_x$ waveguide electro-absorption modulators on silicon and analyze the Franz-Keldysh modulation properties. The introduction of Sn into Ge allows for considerably narrowing the direct bandgap energy, thereby extended the absorption edge toward mid-infrared region to achieve mid-infrared optical modulation. We calculate the change in absorption coefficient of $Ge_{1-x}Sn_x$ induced by the Franz-Keldysh effects. The results show that significant absorption coefficient variation associated with the Franz-Keldysh effect can be achieved for optical modulation in the mid-infrared region.**

I. Introduction

$Ge_{1-x}Sn_x$ alloys have recently been considered a potential material for mid-infrared photonic devices on silicon because of the unique advantages of CMOS compatibility and tunable bandgap energy [1]. Extensive progresses have been made to develop efficient GeSn-based photonic devices with extended operation in the infrared region [2]–[4]. Another indispensable component for photonic systems is optical modulators. In this paper, we present a design of GeSn-based electro-absorption modulators (EAMs) based on Franz-Keldysh (FK) effect for mid-infrared applications, and calculate the changes in absorption coefficient induced by electric fields for estimating the performance of the devices.

II. Device Structure

Figure 1(a) schematically shows the designed $Ge_{1-x}Sn_x$ waveguide optical modulators, consisting a Ge/$Ge_{1-x}Sn_x$/Ge *p-i-n* heterostructure (thickness 200/300/100 nm) pseudomorphically on Si (001) substrates via a fully strain-relaxed Ge virtual substrate (thickness 120 nm). Because of the pseudomorphic growth condition, the $Ge_{1-x}Sn_x$ active layer is subject to a compressive strain of $\varepsilon = -0.143x$. The width of the waveguide is set to $w = 2$ μm and the length is L. Figure 1(b) shows the simulated energy distribution of the waveguide at λ=2000 nm. It is clearly shown light can be properly confined in the waveguide because the large refractive index difference between the *p-i-n* heterostructure ($n \approx 4.2$) and SiO_2 cladding layer ($n = 1.46$) and the silicon substrate ($n = 3.47$). The calculated optical confinement factor for the $Ge_{1-x}Sn_x$ active layer is as high as $\Gamma = 0.329$.

III. Theoretical Models

The strained band structure of $Ge_{1-x}Sn_x$ alloys is calculated using multi-band k·p method, where the strain effect is considered using deformation potential theory [5]. The parameters

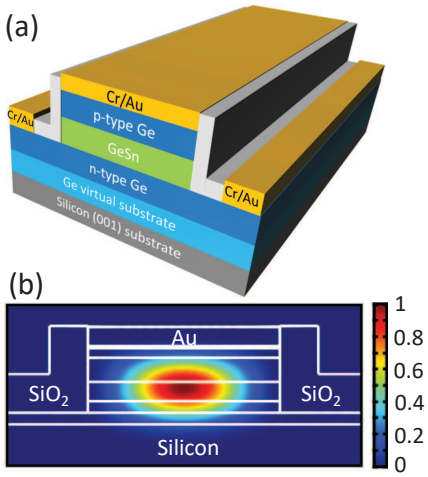

Fig. 1. (a) Our proposed $Ge_{1-x}Sn_x$ *p-i-n* heterostructures for waveguide electro-absorption optical modulators. (b) Simulated energy distribution for the TE fundamental mode at λ=2000 nm.

used in this calculation are taken from Ref. [6]. The position dependent HH and LH bandgap energies in units of eV for pseudomorphic $Ge_{1-x}Sn_x$ on Ge can be described by

$$E_g^{\mathrm{HH}} = 0.8 - 2.732x + 1.702x^2 \quad (1)$$

$$E_g^{\mathrm{LH}} = 0.8 + 1.466x - 0.464x^2 \quad (2)$$

With the bandgap energies, the optical absorption coefficient for an electric field (F) can be calculated using [7]

$$\alpha(\hbar\omega) = \frac{e^2|\hat{e}\cdot P_{cv}|^2}{2n_r c\varepsilon_0 m_0^2\omega}\left(\frac{2m_r}{\hbar^2}\right)^{3/2}\sqrt{\hbar\theta_F}\left[-\eta Ai^2(\eta) + Ai'^2(\eta)\right] \quad (3)$$

$$\hbar\theta_F = \left(\frac{\hbar^2 e^2 F^2}{2m_r}\right)^{1/3} \quad (4)$$

$$\eta = \frac{E_g - \hbar\omega}{\hbar\theta_F} \quad (5)$$

where e is the elementary charge, $|\hat{e}\cdot P_{cv}|$ is the moment matrix element, n_r is the background refractive index, ε_0 is the permittivity, m_0 is the free electron mass, m_r is the reduced mass, and Ai and Ai' are the Airy function and its derivative, respectively. Here the optical absorption coefficient for both HH $\rightarrow c\Gamma$ and LH $\rightarrow c\Gamma$ direct transitions are calculated, and their sum is the total absorption coefficient.

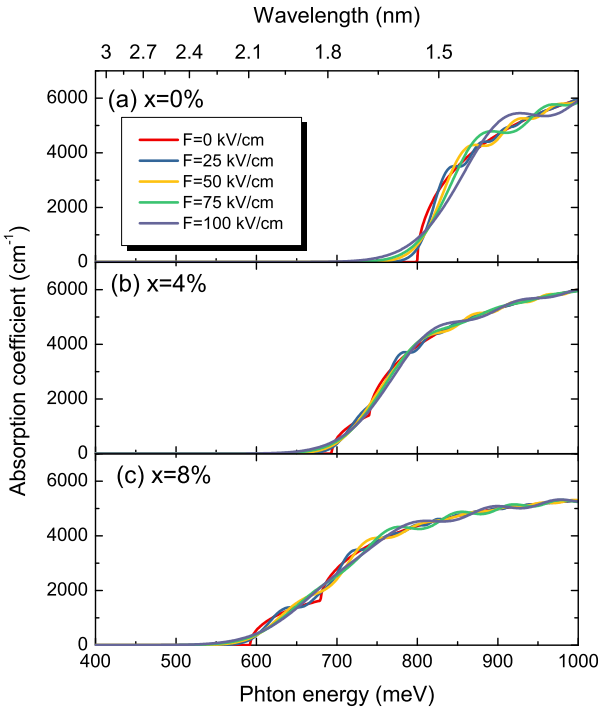

Fig. 2. Calculated absorption spectra for pseudomorphic $Ge_{1-x}Sn_x$ on Ge with different electric field.

IV. Results and Discussions

Fig. 2 shows the calculated direct-gap absorption spectra for pseudomorphic $Ge_{1-x}Sn_x$ on Ge with different electric fields. As the Sn composition increases, the absorption edge shifts to low energies (longer wavelengths) because the introduction of Sn into Ge considerably shrinks the direct bandgap energy. For $x = 8\%$, the direct bandgap energy is reduced from 800 meV to 593 meV, extending the absorption edge into the MIR region (2091 nm). In addition, the HH and LH bands are not longer degenerate because of the compressive strain. As a result, the HH band becomes the lowest valence band and HH $\rightarrow c\Gamma$ direct transition defines the absorption edge of the material. With the application of an electric field, the band structure is tilted. As a result, the absorption coefficient is perturbed and the change in absorption coefficient increases with increasing electric field. Therefore, the absorption coefficient near the band edge can be manipulated for optical modulation. However, it is shown that the change in absorption coefficient near the absorption edge becomes smaller with increasing Sn concentration. This observation is mainly attributed to the HH-LH splitting induced by the compressive strain. As a result, only the HH $\rightarrow c\Gamma$ transition contributes to the optical absorption near the absorption edge.

From the calculated absorption spectra and the optical confinement factor, we estimate the extinction ratio of the $Ge_{1-x}Sn_x$ waveguide electro-absorption optical modulators. The extinction ratio in units of dB can be calculated using $ER(V) = 4.343 \times \Gamma[\alpha(F) - \alpha(0)]L$ [7]. The calculated results for a 40 μm long device with an electric field of

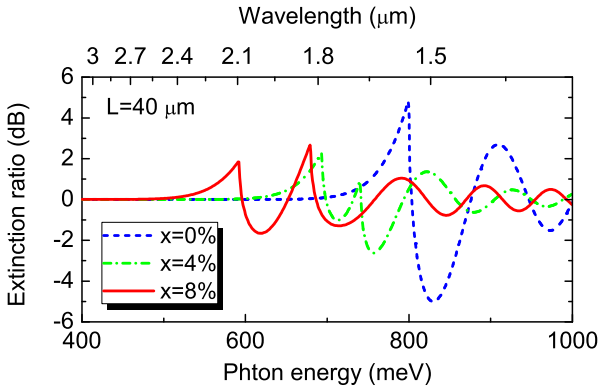

Fig. 3. Calculated extinction ratio spectra for the $Ge_{1-x}Sn_x$ waveguide electro-absorption optical modulators with different Sn composition.

$F = 100$ kV/cm is depicted in Fig. 3. The results that, for $x = 0\%$ (pure Ge), an maximum of 4.83 dB extinction ratio can be obtained at $\lambda = 1540$ nm. As the Sn composition increases, the position of maximum extinction ratio shifts to longer wavelengths, but it magnitude decreases. Nevertheless, optical modulation in the mid-infrared range can be achieved using the proposed $Ge_{1-x}Sn_x$ waveguide modulators, and requires further investigation to improve the performance.

In conclusion, we have present a design and analysis of GeSn-based waveguide electro-absorption optical modulators based on Franz-Keldysh effect. Because of the narrowed bandgap caused by Sn-alloying, the GeSn active layer can achieve significant changes in absorption coefficient in the mid-infrared range in response to an electric field. In addition, the strain effect plays an important role in the strength of the Franz-Keldysh modulation. These results provide useful guidelines for designing and realizing GeSn-based mid-infrared optical modulators for a wide range of applications.

Acknowledgment

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