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Strain tuning of Franz-Keldysh Ge electro-absorption modulation

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1. Introduction

Modulators are the devices widely studied in recent Si photonics. Electro-absorption (EA) modulation based on the Franz-Keldysh effect of Ge [1] has attracted much attention, comparing with electro-refractive Si modulation [2] [3]. Franz-Keldysh Ge EA modulators have recently been reported and demonstrated micrometer footprints, low power consumption (10 – 100 fJ per bit) and operation wavelength around 1.55 μm [4][5]. The challenge is its narrow operation wavelength window ~0.015 μm, leading to the requirements of several SiGe-based modulators working at different wavelength to cover the whole C+L band (1.53 – 1.62 μm). One solution for this issue is using Si_xGe_{1-x} alloys for the modulation, which has indeed been demonstrated in [4]. However, with increasing Si composition, the indirect characteristic of this alloy deteriorates the Franz-Keldysh effect of the absorption coefficient induced by the direct gap. Moreover, a complex processing leads higher cost.

We have proposed a new approach to tune the bandgap of Ge with various strains to cover the whole range of C+L band [6]. Biaxial strain due to the thermal expansion mismatch shifted the absorption edge of Ge epilayer on Si from 1.55 μm to 1.605 μm [7]. It suggests that we can use strain to control the bandgap of Ge, therefore, to tune the operation wavelength of Ge EA modulators. In this paper, we have demonstrated the shift of absorption edge by strain, and also the Franz-Keldysh effect in intentionally strained Ge as a proof of strain-tuning concept.

2. Experimental procedures

We have employed SiN_x as stressors and fabricated free space Ge photodetectors. 400 nm-thick Ge epilayer was grown on a 4 inch p^+-Si(100) substrate by ultra high vacuum chemical vapor deposition (UHV-CVD). Phosphorus donors were implanted to make vertical *p-i-n* diode structures. The phosphorus peak concentration was approximately 10^{20} cm^{-3}. Finally, 500 nm-thick SiN_x films were deposited and patterned to make stressor stripes on Ge photodetectors.

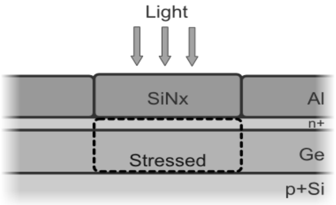


Figure 1. Cross section view of Ge detectors with stressors

We measured the induced strain in Ge by microscopic Raman scattering spectroscopy (μ-Raman), and the photocurrent and responsivity spectra of Ge photodetectors on Si.

3. Strain induced absorption edge shift

The stress profile measured by μ-Raman showed that 200 MPa of tensile stress is applied into the Ge layer. The k·p theory predicted the shift of the absorption edge of Ge with the stressor by an amount of 0.02 μm to the longer wavelength. The responsivity spectra are shown in Figure 2. Our free-space Ge photodetectors on Si with the SiN_x stressors have reproduced the predicted red-shift and covered the L band edge (1.62 μm).

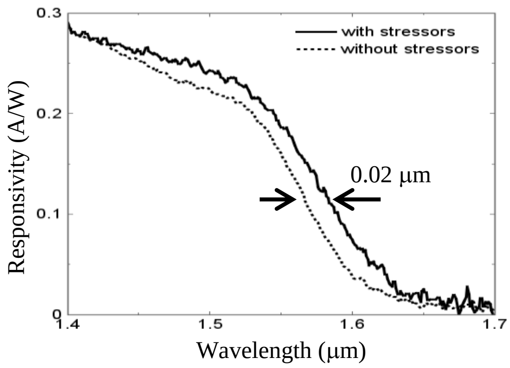


Figure 2. The responsivity spectra of free space Ge photodetectors with and without stressors

4. Franz-Keldysh absorption change in strained Ge

Figure 3 shows typical photocurrent spectra of our Ge photodetectors with the SiN_x stressor under reverse biasing. The change in spectra suggests that there is an electro-absorption effect here.

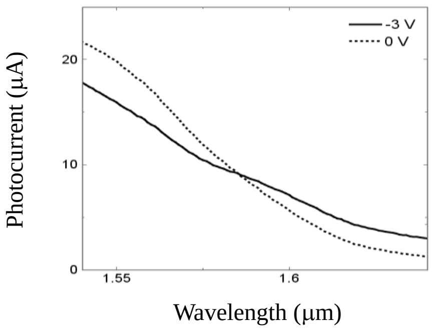


Figure 3. The photocurrent spectra of free space Ge photodetectors with SiN_x stressors.

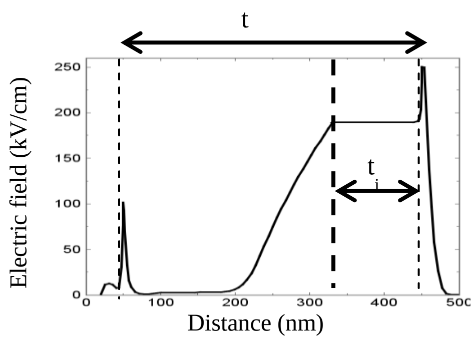
To confirm whether it is due to the Franz-Keldysh effect or not, we compare experiment data with theoretical calculations by the generalized Franz-Keldysh formalism [8].

First, we simulated electric field from the doping profile shown in Figure 4(a) by a one-dimensional finite-difference simulator (PC1D). As in Figure 4(a), 200 nm-thick phosphorus implanted region does not show any change of electric field upon external biasing, but very high electric field in the thinner *i*-region. To keep this in mind, we calculated the absorption coefficient from the photocurrent spectra, and then obtained the figure of merit (FOM) $\Delta\alpha/\alpha$, where $\Delta\alpha$ is the change in absorption coefficient with and without applied bias, and α is the absorption coefficient when there is no external bias. This FOM is very important for EA modulators because $\Delta\alpha$ and α represent extinction ratio and insertion loss of EA modulators respectively. We should point out that absorption coefficient only changes where there is electric field, therefore the FOM should be calibrated as following:

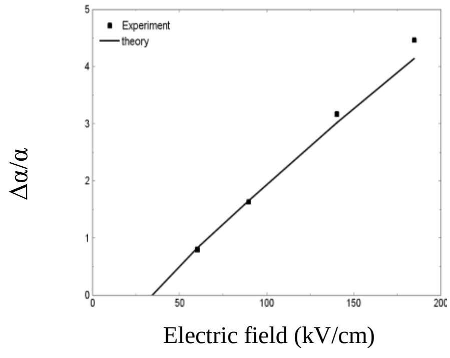
$$\frac{\Delta\alpha}{\alpha}(obs) = \frac{(\alpha(V) - \alpha(0))}{\alpha(0)} \times \frac{t_i}{t}, \qquad (1.1)$$

$$\frac{\Delta\alpha}{\alpha}(cal) = \frac{\Delta\alpha}{\alpha}(obs) \times \frac{t}{t_i}, \qquad (1.2)$$

where t is the total thickness of Ge layer, t_i is the thickness of the *i*-region. $\Delta\alpha/\alpha$(obs) is the FOM calculated directly from photocurrent spectra and $\Delta\alpha/\alpha$(cal) is the FOM after calibration by equation (1.2).



(a)



(b)

Figure 4. (a) The electric field distribution of Ge photodetectors with stressors. (b) $\Delta\alpha/\alpha$ as a function of electric field

Figure 4(b) shows $\Delta\alpha/\alpha$(cal) as a function of electric field. The theory reproduces the experiment data very well, confirming the Franz-Keldysh effect working in our Ge photodetectors.

5. Conclusions

We have demonstrated the strain-induced shift of absorption edge in Ge with the SiN_x stressor, and absorption-modulation in term of the Franz-Keldysh effect using intentionally strained Ge. These are proofs of strain-tuning concept for Franz-Keldysh Ge EA modulators working in C+L band. The EA modulator has various advantages such as smaller footprint, lower power consumption, and higher stability against temperature fluctuation, comparing with Mach-Zehnder modulators and Si microring modulators. The EA modulator will open up a new way to realize high performance electronic-photonic integrated circuits.

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