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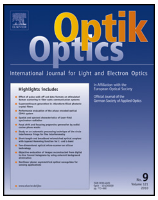

Original research article

The Franz-Keldysh effect and free carrier dispersion effect in germanium

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ABSTRACT

We calculated the changes of refractive index and absorption coefficient in Ge induced by the Franz-Keldysh (FK) effect and free carrier dispersion (FCD) effect, taking advantage of reported absorption spectra.The FK effect is weak near the indirect absorption edge of Ge. FCD effect can induce a much larger change of refractive index. In the wavelength range of 2–10 μm, theoretical formulas about dependences of the changes of absorption coefficient and refractive index on the change of carrier concentrations are presented. In addition, FCD effects in N-type and P-type Ge are compared.

1. Introduction

Germanium (Ge) devices, which can be applied to the silicon-based (Si-based) photonics monolithic integration, are attracting increasing interest in recent years, due to its CMOS compatibility and cost-effectiveness. Ge-on-Si light sources [1,2], modulators [3,4] and detectors [5] operating at 1.5–1.6 μm have already been investigated. Meanwhile, Ge is able to extend the operating wavelength of Si-based modulators from near-infrared to mid-infrared [6,7], since it is transparent for light whose wavelength is more than 1870 nm.

Pockels effect, which is a most proper mechanism for modulators, is theoretically absent in Ge and Si due to the centrosymmetry. As a result, the Franz-Keldysh (FK) effect [8,9] and free carrier dispersion (FCD) effect [10] are usually considered when designing Ge and Si modulators. In 1987, R. Soref et al. investigated the changes of refractive index (Δn) and absorption coefficient ($\Delta\alpha$) of Si induced by the two effects [10], and the results indicated that FCD effect is significant in Si. Subsequently, researchers paid attentions to Si modulation devices based on FCD effect and made a lot of achievements [11–14]. As to Ge, however, studies on the application of the FK effect and FCD effect to optoelectronic devices are not sufficient. Recently, M. Nedeljkovic et al. [15] predicted free-carrier electroabsorption and electrorefraction in doped Ge based on the first principle quantum theoretical modeling. They neglected FK effect and the contribution of charged impurities to the change of refractive index in the final calculation.

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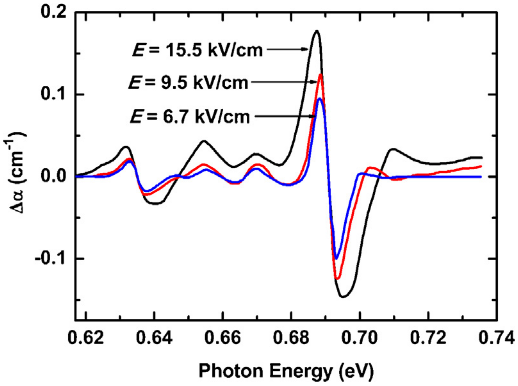

Fig. 1. Change of absorption coefficient near the indirect absorption edge of Ge with different electric field intensities [18].

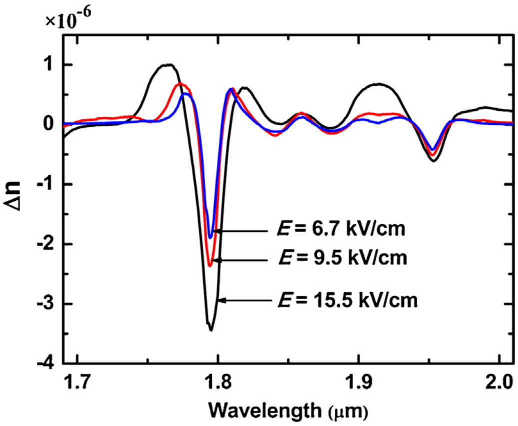

Fig. 2. Change of refractive index near the indirect absorption edge of Ge v.s. the wavelength.

In this paper, based on the experimental data in literatures, we calculated the refractive index perturbations in Ge induced by FK effect near the indirect absorption edge and by FCD effect in mid-infrared region at room temperature. Especially for FCD effect, the change of refractive index of Ge in the wavelength range from 2 to 15 μm is given here, and empirical equations about dependences of $\Delta\alpha$ and Δn (or $-\Delta n$) on changes of impurity concentrations (ΔN) at wavelength of 2–10 μm are summarized.

2. Franz-Keldysh effect

A. Frova et al. directly observed FK effect in reverse-biased Ge P-N junctions [16,17] and measured the change of absorption coefficient under different electric fields near the indirect absorption edge of Ge [18]. They neglected carrier effects and dissipated the Joule heat effect by water cooling. The $\Delta\alpha$ curves (ref. [18], Fig.5) were digitized with a step length of 0.24 meV and extrapolated to zero in lower photon energy region, as shown in Fig. 1. Thus, the change of refractive index of Ge can be calculated according to the numerical integration as follow [10],

$$\Delta n = 6.3 \times 10^{-6}\,(\mathrm{cm}\cdot\mathrm{V})\,P.V.\int_0^{\infty} \frac{\Delta\alpha(V')}{V'^2 - V^2}\mathrm{d}V', \tag{1}$$

where$P.V.\int_0^{\infty}$ stands for the Cauchy principal value integral and $V = \hbar\omega/e$ is a normalized photon energy, $\hbar$ is the reduced Planck constant, and ω is the light frequency.

The Δn curves are shown in Fig. 2. When the electric field intensity E is 15.5 kV/cm, $\Delta\alpha$ is 0.18 cm^{-1} and Δn is -3.5×10^{-6} at 1.79 μm. The dependence of Δn at 2 μm on the electric field was shown in Fig. 3. According to the fitted curve in Fig. 3, when $E = 10^5$V/cm, Δn is only 4.3×10^{-4}. As a comparison, Δn near the direct absorption edge of Ge with an electric field of 10 kV/cm were also calculated, according to the $\Delta\alpha$ data in ref. [19], which is shown in Fig. 4. Δn is -4.5×10^{-3} at 1.55 μm, which is much larger than that induced by the FK effect near the indirect absorption edge. The FK effect near the direct absorption edge is useful for the Ge photodiodes at the wavelength from 1.5 to 1.6 μm [20,21]. However, it may be not proper for the application to Ge modulators, for the large absorption loss at 1.55 μm and the weak performance near the indirect edge.