Optical Rectification in surface layers of germanium

Li Zhang, Qi Wang and Zhanguo Chen*
State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, 2699 Qianjin Street, Changchun 130012, People's Republic of China

* Email: czg@jlu.edu.cn; Tel.: +86-0431-85168382

This paper reports a preliminary study of electric field induced (EFI) optical rectification (OR) in (001), (110) and (111) surface layers of germanium (Ge). It is well known that the second-order nonlinear optical effects are theoretically absent in Ge due to the inverse symmetry. In fact, space charge regions (SCRs) exist in surface layers of Ge, and electric fields in SCRs can break the inverse symmetry and induce the so-called "EFI OR". OR is an important mechanism to be used in terahertz (THz) generation. A. Urbanowicz et al. indicated that EFI OR played an important role in the observed THz emission from Ge surfaces [1]. Besides, EFI OR can be used to characterize surface properties of crystals with symmetry centers such as Si [2]. We have demonstrated EFI OR in Si(001) surface layers in previous work [3]. However, there are few relative researches on OR in Ge.

The samples used in experiments are all near-intrinsic Ge single crystals, sandwiched between two metal electrodes. The structures, sizes and orientations of the sample are shown in Fig. 1, as well as the measurement system. The thickness of Ge(001) and Ge(110) crystals is 3 mm and the resistivity is about 60 Ω·cm. The thickness of Ge(111) crystals is 1 mm and the resistivity is more than 35Ω·cm. The light source is a fiber laser with the wavelength of 1964 nm. A chopper is used to input a reference signal into the lock-in amplifier. The polarization of the polarizer is along the x axis. If the azimuth of linearly polarized light with respect to the x axis is θ, when the light propagated along the y axis, the dc polarization along the z axis can be expressed as,

$$P_z(0) = \varepsilon E^2(\omega)\{[\chi_{zxx}^{(2eff)} + \chi_{zzz}^{(2eff)}] + [\chi_{zxx}^{(2eff)} - \chi_{zzz}^{(2eff)}]\cos 2\theta\}, \tag{1}$$

where ε is the permittivity of Ge, $E(\omega)$ is the optical electric field of the probing beam, and $\chi_{zxx}^{(2eff)}$ and $\chi_{zzz}^{(2eff)}$ are the components of the effective second-order susceptibility tensor. By rotating the half-wave plate, we measured the dependence of OR signals on the azimuth θ. The OR signals in Ge(001), Ge(110) and Ge(111) surface layers are shown in Fig. 2 to Fig. 4. According to fitted curves, OR signals all show cosine dependences on the azimuth θ. In Fig. 2, the fitted curve can be written as,

$$V_{OR} = 14.05 + 0.6\cos[2(\theta - 30)]. \tag{2}$$

If any contribution to OR signals from absorption is neglected, according to Eqs. (1) and (2), the ratio of $\chi_{zzz}^{(2eff)} / \chi_{zxx}^{(2eff)}$ in Ge(001) surface layer is calculated to be about 0.91, which means that the two susceptibilities are close. Therefore, the sum of the two susceptibilities is much larger than the difference and there is a large background in the measured OR signals. Using the same method, the ratio of $\chi_{zzz}^{(2eff)} / \chi_{zxx}^{(2eff)}$ in Ge(110) and Ge(111) surface layers are calculated to be 0.91 and 1.07.

We also measured the distribution of OR signals in Ge(001) surface layers along the surface normal direction. The result is shown in Fig. 5, as well as the simulation curve, which agrees well with the experimental data. Distance between the two peaks of OR signals is 2920 μm, which is consistent with the thickness of crystal after being polished. According to the simulation, the ratio of the maximum electric field intensities and the ratio of the width of SCRs in No. 1 and No. 2 Ge(001) surface layers are both deduced to be 1:0.966. It is proved that EFI OR is a method to analysis the surface properties of crystals with symmetry centers, such as Ge and Si.

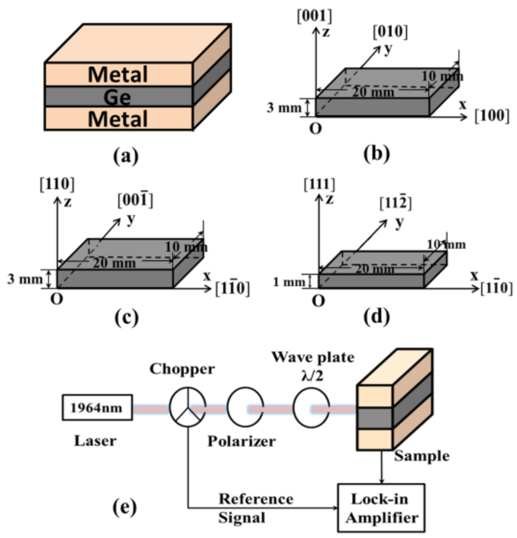

Fig.1 Structures, sizes and orientations of Ge samples, as well as the measurement system of OR. (a) Sample structure, (b) Ge(001) crystal, (c) Ge(110) crystal, (d) Ge(111) crystal, (e) measurement system.

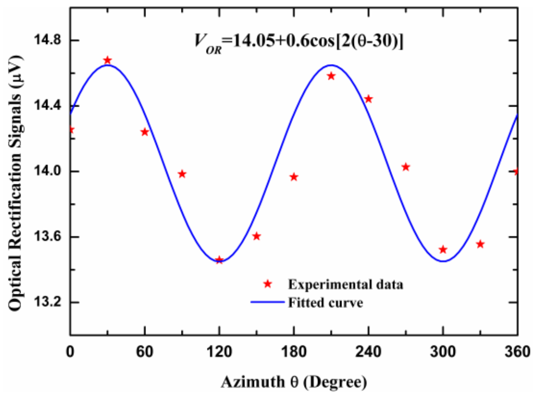

Fig. 2 OR signals in the Ge(001) surface layer.

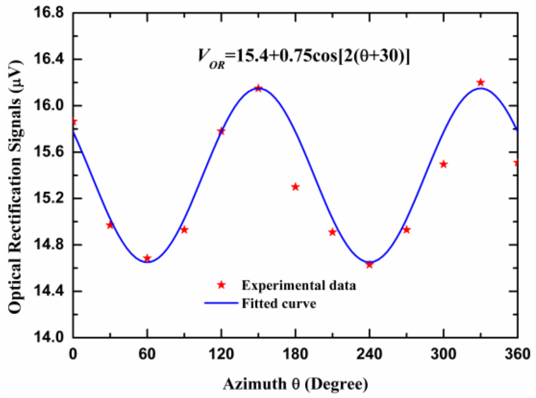

Fig. 3 OR signals in the Ge(110) surface layer.

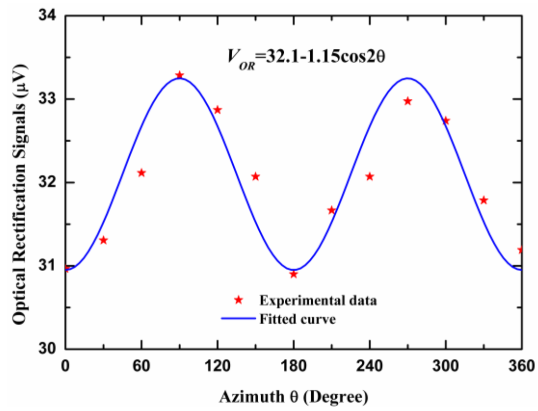

Fig. 4 OR signals in the Ge(111) surface layer.

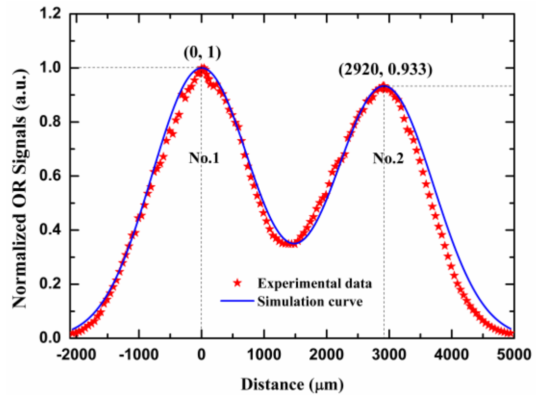

Fig. 5 Distribution of OR signals in Ge(001) surface layers along the surface normal direction.

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