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Effect of modulation of ultrafast transient carrier dynamics by interface on terahertz signal

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Abstract. The carrier dynamics in the nanostructured semiconductors related to the drift and diffusion currents strongly affects the device performance, such as the efficiency of the carrier injection into the active layer. We report on the effects of the photocurrent direction on the THz signals emitted from the GaAs crystal including an interface. The polarity inversion of the signal is caused by the change in photocurrent direction from diffusion to drift. The inversion is not affected by electron lifetimes. These results suggest that measurement of the THz wave is useful to consider the photocurrent direction.

1. Introduction

The light emitting devices based on the semiconductor quantum dots (QDs), such as the QD lasers in the ultrafast optical telecommunication systems [1-3] and the single photon sources in the information communication systems [4-6], have been studied. In general, the self-assembled QDs are grown in the Stranski-Krastanov mode, so that the potential is modulated by the lattice-mismatched strain [7, 8]. The potential modulation due to the strain, which changes the current injection direction, is important when the efficiency of QD based devices is considered. The carrier dynamics, in particular, injection process to InAs QDs from GaAs has been discussed from the results measured by a pump-probe technique [8, 9] and the time-resolved photoluminescence spectrum [10, 11]. On the other hand, it is difficult to directly define the direction of carrier diffusion using these techniques.

On the other hand, the observation of THz time-domain signals emitted from the semiconductor surfaces provides the diffusion direction of carrier excited by the ultrashort pulse lasers [12-14]. For instance, in the n-type (p-type) semiconductors the THz signal shows the initial increase (decrease), which originates from difference in the diffusion direction; from the surface to the substrate (from the substrate to the surface). Therefore, the effects of the potential modulation caused by the lattice-mismatched strain on the carrier diffusion direction can be revealed by measuring the THz time domain signal [15]. In this work, we demonstrate the calculation results of the THz signal emitted from the GaAs crystal including an interface, which causes the potential modulation, near the surface. The origins of THz signal are divided into two parts; from the surface to the interface and from the interface to the surface. When the direction of photocurrent in the deeper region is changed, the polarity of the THz signal is inverted. This inversion is discussed from the aspects of the balance between the diffusion and drift, and carrier lifetimes.

2. Calculation method

In the calculation of the THz signals, the potential structure shown in figure 1 was assumed for simplicity. In the GaAs crystal with the total thickness of 650 nm, the interface modulating the potential locates at 150 nm from the surface, which is similar potential structure including the δ-doping layer. In the calculation, the weak electric field was considered. Hence, the overshoot is not caused. The region from the surface to the interface and that from the interface to the bottom are referred as L_1 and L_2, respectively. In the L_1 region, the electrons move toward the interface due to the diffusion and drift. On the other hand, in the L_2 region, while the electrons move to the substrate due to diffusion, those move toward the interface due to drift. The photocurrent generated by ultrashort pulse can be expressed as follows [10]. The signal rise was considered by Gaussian profile.

$$J(t) \propto \frac{e^{-\frac{\gamma t}{2}}}{t}\left\{\sin\left(\frac{\omega_0+\omega_{L1}}{2}\right)\sin\left(\frac{\omega_0-\omega_{L1}}{2}\right) - B\sin\left(\frac{\omega_{L1}+\omega_{L2}}{2}\right)\sin\left(\frac{\omega_{L1}-\omega_{L2}}{2}\right)\right\}, \quad (1)$$

where $\omega_0 = (\omega_{exc}^2 - \gamma^2)^{\frac{1}{2}}$, $\omega_{L1} = \left(\omega_{exc}^2 \exp(-\alpha L_1) - \frac{\gamma^2}{4}\right)^{\frac{1}{2}}$ and $\omega_{L2} = \left(\omega_{exc}^2 \exp(-\alpha L_2) - \frac{\gamma^2}{4}\right)^{\frac{1}{2}}$.

And $\omega_{exc} = \left(\frac{e^2 n_{exc}}{\kappa\kappa_0 m^*}\right)^{\frac{1}{2}}$ is the plasma frequency of photoexcited carriers at the surface. α is the absorption coefficient in the GaAs crystal. κ and κ_0 are the relative permittivity and permittivity of vacuum, respectively. m^* is the reduced mass of an electron-hole pair in GaAs crystal, and e is the elementary charge. n_{exc} is the density of photoexcited electron-hole pairs at the surface. In the calculation, parameters $n_{exc}=1\times10^{17}$ cm^{-3}, $\gamma=5$ ps^{-1}, $\alpha=1.3$ μm^{-1}, $\kappa=12.9$ and $\kappa_0=8.8\times10^{-11}$ m^{-3}kg^{-1}s^{4}A^2 were used [16-18]. Here, the parameter B expresses the ratio of drift and diffusion in the L_2 region in figure 1. The THz signals were obtained by numerical differentiation of the equation (1).

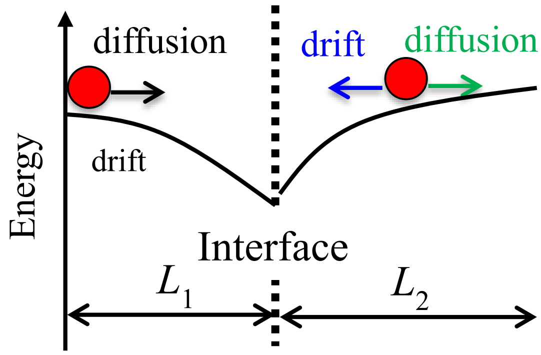

Figure 1. The potential structure for calculations. The dotted line locates on the interface. In the L_2, the direction of carrier movement by drift and diffusion is opposite.

3. Results and discussion

Figure 2(a) indicates the dependence of the THz signals on the value of B. At B=0 there is no contribution of the carriers in the L_2 region; the signals results from the photocurrent only in the L_1 region. Decreasing B, which corresponds to an increase in the contribution due to diffusion current from the L_2 region, the amplitude of the signal gradually increases. On the other hand, increasing B, which increases the drift current from the substrate to the surface, the amplitude decreases until B=0.5 and then increases.

Focusing on the amplitude at t=0 in figure 2(a), the polarity of the signal is inverted from positive to negative. To clarify the polarity inversion, the amplitude at t=0 of the THz signals was plotted in figure 2(b) by closed circles. Increasing the value of B is the amplitude monotonically decreases and the polarity inversion occurs at around B=0.6. Furthermore, the frequency changes at B=0.6 where polarity inversion, as shown in figure 2(b) by open circles. Here, the frequency is much larger than the reported experimental values. The frequency in equation (1) is sensitive to n_{exc}. Therefore, the calculated frequency may not be correct. However, the dependence on B is considered to be worth discussing. The polarity inversion does not originate from the initial carrier distribution due to the light absorption. As indicated in figure 2(c), the initial carrier distribution in the L_1 and L_2 regions are hardly changed. The vertical line shows the location of the interface. The light intensities with the photon energies of 1.38 eV, 1.46 eV and 1.55 eV in a GaAs crystal calculated using the absorption coefficient [18] were indicated by the gray, dotted and solid curves, respectively. Considering the number of carriers generated by ultrashort pulse depending on the light intensity, there is no remarkable difference in the photon energies. Therefore, as the physical mechanism to invert the polarity of THz signals, the effect of the potential modulation caused by the interface was considered.

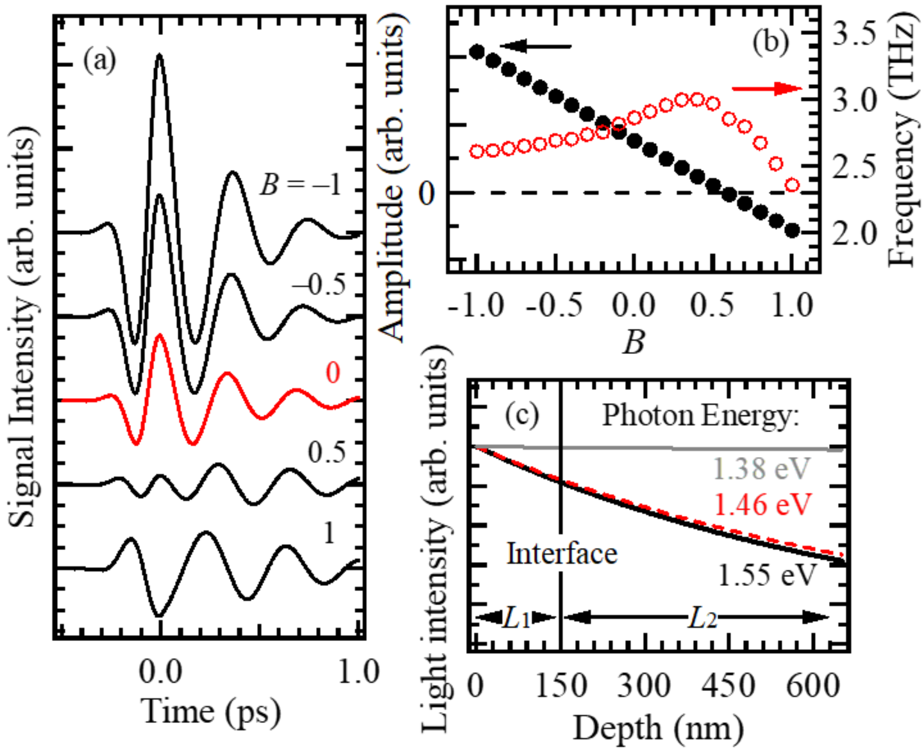

Figure 2. (a) The THz signal calculated for various *B* values. (b) The amplitude at t=0 and the frequency were plotted by the closed and open circles, respectively. (c) The light intensity profile in the GaAs crystal calculated for the light with the energies of 1.38 eV, 1.46 eV and 1.55 eV. The vertical line indicates the position of the interface.

The polarity inversion is not changed by the carrier lifetimes. The terahertz signals depending on the electron lifetime calculated for the various *B* values are shown in figure 3(a), 3(b) and 3(c). Clearly, the signal does not depend on the electron lifetimes. In the case of γ_{L2}=2.0 γ_{L1}, although electron in the L_2 region disappears much faster than that in the L_1 region. That signal inverted in the case of B=1. Furthermore, in all conditions, the variation of the electron lifetimes in the L_2 region hardly changes the signal amplitude. Our results suggest that the measurement of time-domain THz signal can give important information about the current direction in the deeper area.

4. Conclusion

We have investigated the effects of the change in the photocurrent direction on the THz signal emitted from the semiconductor surface, which caused by the interface. When the drift current increases in the region underneath the interface, the polarity of the THz signal was inverted. On the other hand, the signal, including polarity inversion, hardly depends on the electron lifetime. These results suggest that measurement of the THz wave is useful to consider the photocurrent direction and contributes to improve the efficiency of the devices based on QDs.

Acknowledgments

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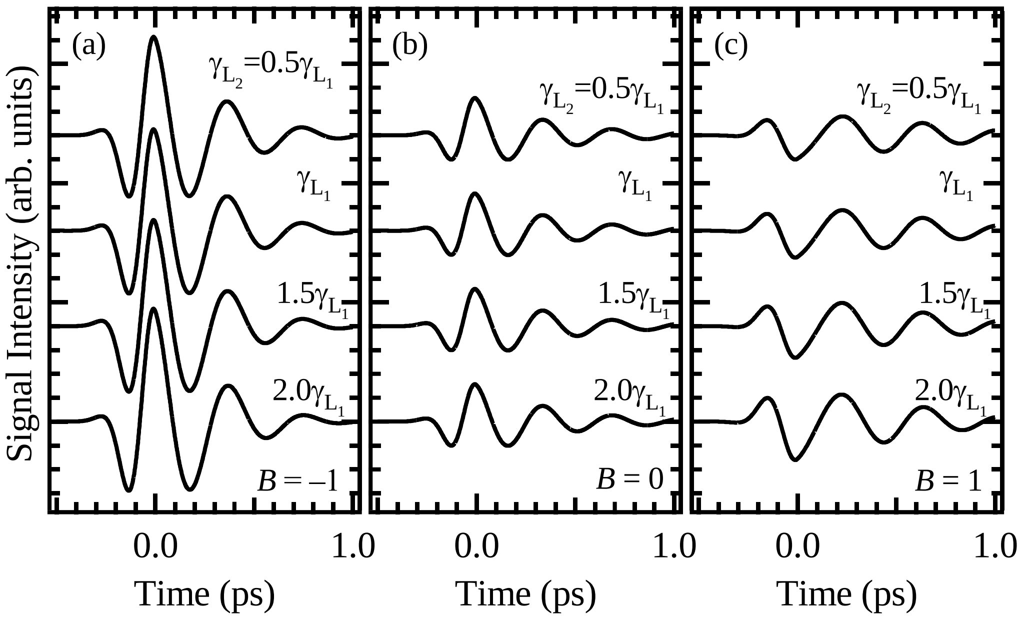

Figure 3. The THz signals calculated for various ratios of γ_{L2} and γ_{L2}. In the cases (a) B= −1, (b) B=0 and (c) B=1.

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