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Investigation of Ultrafast Carrier Dynamics in Quantum Wire by Terahertz Spectroscopy

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1. Introduction

In recent years, measurements of ultrafast carrier dynamics using terahertz (THz) wave spectroscopy have been studied actively.[1,2] In this technique, velocity of carriers, dephasing time, T_2, and Bloch oscillations can be measured by the analysis of observed THz wave. In this paper, we report an investigation of ultrafast carrier dynamics in a crescent-shaped quantum wire structure using the THz wave spectroscopy.

2. Sample Structure

A GaAs/AlGaAs crescent-shaped quantum wire sample used in our experiment was fabricated on a V-grooved GaAs substrate by the metalorganic chemical vapor deposition (MOCVD) growth method with flow rate modulation epitaxy (FME) technique[3,4]. Fifteen periods of very small crescent-shaped quantum wires with a central thickness of 11nm and a lateral full width of 46nm were formed at the bottom of the V-groove as shown in Fig. 1. More detailed description of the sample structure and a PL and PLE spectra were shown in Ref. 3 and 4.

3. Mechanism of THz Wave Generation

THz waves are generated by the time evolution of coherent polarization, $P(t)$, induced by ultrashort optical pulse excitation. In the crescent-shaped quantum wire structure, the gravity centers of electrons and holes are different due to the structural asymmetry as shown in Fig. 2, so that the crescent-shape structure induces self-polarization in the quantum wire. The coherent polarization is given by

$$P(t) = |e| \sum_k \left[(z_{22} - z_{11})\rho_{11}(t) + (z_{33} - z_{11})\rho_{11}(t) - 2z_{23}\,\mathrm{Re}(\rho_{23}(t)) \right], \qquad (1)$$

where ρ_{nm} is the probability density of the excitons between energy states m and n (Fig. 3), and z is the displacement of the electron described by $z = \langle \phi_n | z | \phi_m \rangle$. The first and second terms imply an instantaneous polarization formed by electron-hole pairs. The third term implies quantum beats between heavy holes and light holes. The electric field of THz waves generated by P is given by

$$E_{\mathrm{THz}} = \frac{\partial^2 P}{\partial t^2}. \qquad (2)$$

4. Experimental Results and Discussions

THz waves generated from the quantum wire sample were measured by a free-space electrooptic (EO) sampling method. The precise method of free-space EO sampling is shown in Ref. 4 and 5.

Figure 3 (a) shows time-resolved THz waveforms as a function of the excitation wavelength. The amplitudes of the THz waves depend on the excitation wavelength, which was at maximum at wavelength of 808nm.[7] The electric field of the THz wave is defined by Eqns. 2, so that integration of observed THz waves shows time evolution of the polarization in the quantum wire, namely,

$$P(t) = \iint E_{\mathrm{THz}}(t)dt^2. \qquad (3)$$

Figure 4 shows integrated waveforms of each THz wave shown in Fig. 3. Dephasing time of the coherent polarization became shorter with increasing the excitation energy. This is resulted from the carrier-carrier scattering of the excited carriers. It was estimated that the dephasing time of the coherent polarization at an excitation energy of 1.534eV is 300fs.

5. Conclusion

We have investigated ultrafast carrier dynamics in a crescent-shaped quantum wire by THz wave spectroscopy. The time evolution of coherent polarization is obtained by integration of observed THz waves. Dephasing times of the coherent polarization in the quantum wire was varied with increasing the excitation energy. It was estimated that the dephasing time of the coherent polarization at an excitation energy of 1.534eV is 300fs.

References

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Fig. 1 Cross-sectional SEM image of the quantum wire sample. Very small crescent-shaped quantum wires with a central thickness of 11nm and a lateral full width of 46nm were observed.

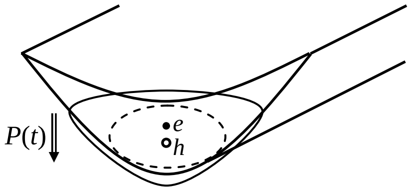

Fig. 2 The self-polarization of the crescent-shaped quantum wire. The gravity centers of the electron (closed circle) and the hole (open circle) are different, because the wave function of the electron (solid curve) is broader than that of the hole (dotted curve).

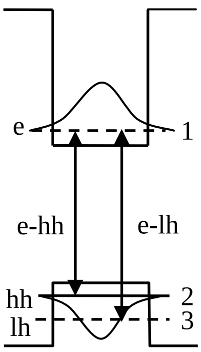

Fig. 3 Schematic energy level diagram of the quantum wire

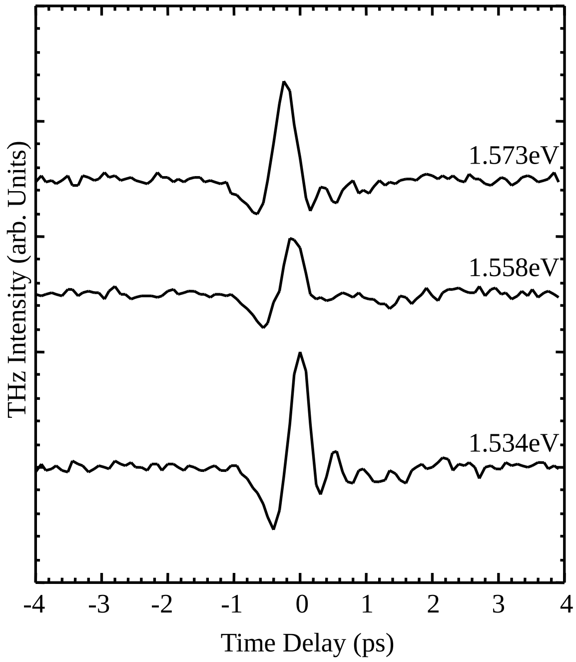

Fig. 4 Time-resolved THz waveform as a function of the excitation wavelength.

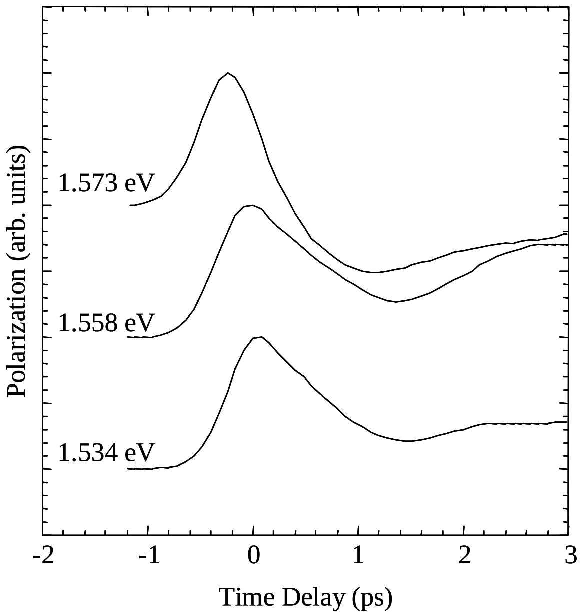

Fig. 5 Time evolution of the coherent polarization obtained by integration of observed THz waveforms.