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Measurement of carrier concentration captured by InAs/GaAs quantum dots using terahertz time-domain spectroscopy

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The authors investigated the carrier dynamics of *n*-type modulation-doped InAs/GaAs quantum dots (QDs) using terahertz time-domain spectroscopy to estimate the total number of electrons captured by the QDs. The terahertz power absorption of the sample with QDs was less than that of the sample without QDs. This is attributed to the fact that the carriers are confined in the QDs. The experiment results were fitted into the Drude model and the number of electrons captured by QDs was determined through the difference in the numbers of free electrons of the samples with and without QDs. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2716859]

Self-assembled semiconductor quantum dots (QDs) have attracted considerable attention due to their three-dimensional confinement of carriers and atomlike density of states, which enable optoelectronic devices such as laser diodes, semiconductor optical amplifiers,[1] and infrared photodetectors to perform better. For the device applications, modulation doping to the QD structure has been widely used not only to supply carriers to the QDs for the quantum dot infrared photodetector[2] (QDIP) but also to supply excess holes in the valence band of the QD structure for the high modal gain of the ground state in the quantum dot laser diode with a high degree of thermal stability.[3] The carriers from the modulation-doped layer can be captured by the wetting layer and the QDs. However, the carriers captured only in the QDs enable QD-based optoelectronic devices to assume their proper roles, and the carriers captured by the wetting layers can worsen device performance such as in the case of a high dark current in QDIPs. Therefore, it is important to know how many electrons or holes are supplied to the QDs from the modulation-doped layers for the QD device applications to yield higher device performance with an optimum doping level in the modulation-doped layer. However, it is difficult to know how many electrons or holes supplied to the QD structure are captured by the QDs and the wetting layer.

The free carriers in the two-dimensional wetting layer of the QD structure are easily mobile and considerably interact with electromagnetic waves, which results in electromagnetic absorption. However, the carriers captured in the three-dimensional QDs are immobile in external electromagnetic fields and are transparent if the energy of electromagnetic waves is smaller than the energy levels of the QDs. Therefore, terahertz time-domain spectroscopy (TDS) characterizes well the carrier dynamics of the modulation-doped QD structure because it uses low-energy (below 12 meV) electromagnetic pulses.

Terahertz TDS has been a useful technique in the study of carrier dynamics in doped semiconductors between 1 and 10 THz because the terahertz wave interacts well with the mobile carriers.[4] Terahertz TDS generally has a higher signal-to-noise ratio ($>1:5000$) than Fourier transform infrared (FTIR) spectroscopy in this region that has been used as a far-infrared light source for a long time.[5] Particularly, terahertz TDS directly measures the phase information as well as the amplitude because it uses coherent pulses. Therefore, no iterative fitting process, such as the Kramers-Kronig relation that was used to get the phase information in the FTIR spectroscopy, is required in terahertz TDS, but the accurate complex optical constants can be obtained.

In this letter, we describe our investigation of the carrier capture behavior of *n*-type modulation-doped InAs/GaAs QDs using terahertz TDS and estimate the average number of electrons localized in the InAs QDs at room temperature.

We generated and detected terahertz electromagnetic pulses using the photoconductive switching and sampling techniques, respectively.[6,7] The optical pulses used to excite and probe terahertz electromagnetic waves were 80 fs optical pulses at a wavelength of 800 nm from a mode-locked Ti:sapphire laser. The pulses were divided into two beams, which were focused on the generator that was made of Ti/Au coplanar lines on a GaAs substrate and on the detector that was made of a 5 μm dipole gap on a low temperature grown GaAs substrate.[8,9] The terahertz signals were measured by sampling of the convolution signals of the detector gate pulse and the terahertz pulse at the detector. The sample held on a 7 mm diameter aperture was located between two parabolic mirrors that guided the terahertz pulses in free space. The entire terahertz setup was in a dry, airtight box to avoid the effects of water vapor absorption of the terahertz beams.

Two samples with 30 pairs of modulation-doped layers were prepared, as shown in Fig. 1; one was with QDs (1) and the other was without QDs (2). Each modulation-doped QD layer sequentially consisted of an InAs/GaAs QD layer, a 12 nm thick GaAs cap, a 3 nm thick Si-doped GaAs ($n=1\times10^{18}$ cm^{-3}), and a 60 nm thick GaAs layer. These 30-pair layers are on the 50 nm thick GaAs layer, GaAs

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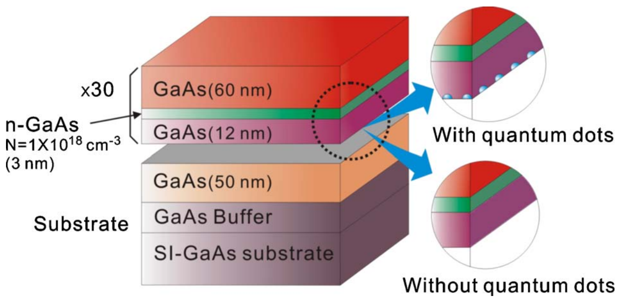

FIG. 1. Structure and dimension of each sample.

buffer layer, and a 450 μm GaAs substrate as the bottom. The sample without QDs had the same layers in the modulation-doped structure, except for the QD layer.

To obtain the absorption by the sample, two kinds of signals were measured. The one used as a reference signal was the signal that passed through an undoped GaAs substrate, and the other was the signal that passed through the sample with modulation-doped layers. The amplitude and phase of the reference signal decreased and was delayed, respectively, after the passage through the modulation-doped layers. These time-domain wave forms were converted into frequency-domain signals through fast Fourier transformation. Generally, the amplitude reduction and the phase difference per sample thickness corresponded to the power absorption and the index of refraction, respectively. These relations are expressed by

$$E_{\mathrm{output}}(\omega) = E_{\mathrm{input}}(\omega) A_{\mathrm{Fresnel}}(\omega) \exp\left(-\frac{d\alpha(\omega)}{2}\right) \times \exp\left(i\frac{2\pi}{\lambda} n(\omega) d\right) \mathrm{FP}(\omega), \tag{1}$$

in which $E_{\mathrm{output}}(\omega)$ is the output signal that passed through the sample, $E_{\mathrm{input}}(\omega)$ is the input signal that was used as a reference, A_{Fresnel} is the Fresnel reflection term due to the difference of refractive indices between the substrate and modulation-doped layer, $\alpha(\omega)$ is the power absorption, λ is the wavelength, $n(\omega)$ is the index of refraction, d is the sample thickness, and $\mathrm{FP}(\omega)$ is the term for the Fabry-Pérot effect in the modulation-doped layers. If the sample thickness is thinner than the wavelength and the power absorption of the sample is not too large to ignore multiple reflections from both sides of the sample, there is an overestimation of the absorption and phase shift. Therefore, the Fabry-Pérot (FP) effect due to the multiple reflections must be eliminated. In our samples, the thickness of the sample except that of the substrate was less than the wavelength, which was from 100 μm to 1.5 mm, and the transmission of the terahertz pulse peak of the thin multilayer sample was 75% as much as that of the GaAs substrate that served as a reference. Therefore, we removed the FP effect to extract the power absorption and the phase difference.[10] The real index of refraction and power absorption are shown in Figs. 2(a) and 2(b), respectively. The power absorption coefficient α is proportional to the imaginary index of refraction as $\alpha = n_i 4\pi/\lambda$, and the frequency-dependent complex index of refraction is represented by $n(\omega) = n_r(\omega) + i n_i(\omega)$. The square of the complex index of refraction is the complex dielectric constant $\varepsilon(\omega) = \varepsilon_r(\omega) + i\varepsilon_i(\omega)$. The complex dielectric constant $\varepsilon(\omega)$ is

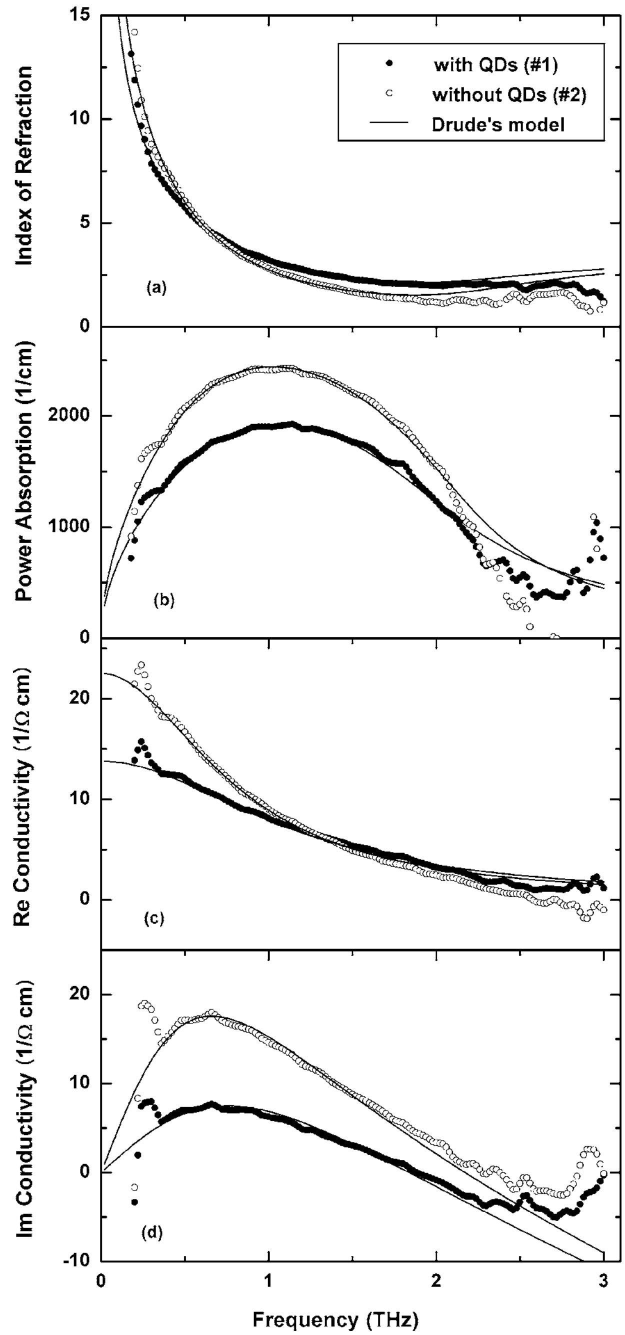

FIG. 2. (a) Absorption coefficient, (b) index of refraction, (c) real conductivity, and (d) imaginary conductivity. The open circles represent the data without quantum dots and the closed circles represent the data with quantum dots. The solid lines represent the fit into Drude's model.

related to the frequency-dependent complex conductivity $\sigma(\omega)$ as shown below:[11]

$$\varepsilon(\omega) = \varepsilon_{\mathrm{GaAs}} + \frac{i\sigma}{\omega\varepsilon_0}, \tag{2}$$

in which $\varepsilon_{\mathrm{GaAs}}$ is the frequency-dependent dielectric constant of the undoped GaAs and ε_0 is the free-space permittivity in a vacuum. The real and imaginary parts of the conductivity in the 0.2–3 THz region are shown in Figs. 2(c) and 2(d), respectively. Sample 1 shows relatively lower power absorption and imaginary conductivity than sample 2. These results imply that the number of electrons or their mobility in sample 1 was smaller than in sample 2. In other words, the QDs acted as charge traps, and therefore, the electrons con-

TABLE I. Drude's model fitting parameters. ω_p is the plasma frequency (THz), Γ the damping rate (THz), N the carrier density ($\times 10^{16}$ cm^{-3}), N_S the carrier density per unit area ($\times 10^{11}$ cm^{-2}), and μ the mobility (cm^2/V s).

Parameter	$\omega_p/2\pi$	$\Gamma/2\pi$	N	N_s	μ
With QDs	7.59	1.16	4.79	1.07	3.601
Without QDs	8.10	0.81	5.45	1.23	5.157

fined in the QDs were not mobile under the influence of terahertz electromagnetic waves.

To obtain the number and the mobility of free electrons, we applied Drude's model, which is related to the complex conductivity $\sigma(\omega)$ as follows:[12]

$$\sigma(\omega) = i\varepsilon_0\omega_p^2/(\omega + i\Gamma), \tag{3}$$

in which ω_p and Γ are the plasma frequency and the damping rate, respectively. These parameters were obtained from the model fit to the experiment results shown in Fig. 2. The plasma frequency yields the carrier density N with a relation of $\omega_p^2 = Ne^2/\varepsilon_0 m^*$, in which e is the unit charge and m^* is the effective mass of the electrons. The damping rate Γ is inversely proportional to the average collision time τ and yields the mobility at a relation of $\mu = e/m^*\Gamma$. The fitting parameters are shown in Table I. The plasma frequencies are 7.59 and 8.10 THz and the damping rates are 1.16 and 0.81 THz for samples 1 and 2, respectively. The plasma frequencies correspond to the electron densities at room temperature of 4.79×10^{16} and 5.45×10^{16} cm^{-3} for samples 1 and 2, respectively. The difference between the electron densities of the samples with and without QDs corresponds to the number of electrons captured by the QDs. Considering the total thickness of the epitaxial layers and the modulation-doped layers, the electron density trapped by the InAs/GaAs QD layer at room temperature is deduced to be 1.6×10^{10} cm^{-2}. Therefore, it was found to be every one of two or three QDs that captured electrons at room temperature, because the density of the QDs was 4.1×10^{10} cm^{-2}. The damping rate Γ explains the carrier-phonon collision dynamics.[13] The damping rate of the sample with QDs was larger than that of the sample without QDs. This implies that there were more carrier-phonon collisions in the sample with QDs than in the sample without QDs, and that the QDs served as scattering centers. This result is also represented by the reduction of mobility from 5157 to 3601 cm^2/V s in samples 2 and 1, respectively.

In conclusion, we measured the complex optical and electrical constants of the samples with and without QDs in the terahertz region, the energy of which was smaller than the energy levels of the QDs. The power absorption and the conductivity of the sample with QDs were found to be less than those of the sample without QDs, because the QDs worked as electron traps and captured the mobile carriers. The carrier densities and mobilities of the samples with and without QDs were obtained using the Drude model fit. Comparing the carrier densities with and without QDs, the carrier concentration captured by QDs was determined. It was also found that the damping rate increased due to the scattering by QDs.

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