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Transient Photoconductivity in InGaN/GaN Multiple Quantum Wells, Measured by Time-resolved Terahertz Spectroscopy

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***Abstract*—Terahertz conductivity of InGaN/GaN MQWs was studied by time-resolved terahertz spectroscopy. Restoration of the built-in piezoelectric field leads to a nonexponential carrier density decay. Terahertz conductivity spectrum is described by the Drude-Smith model.**

I. Introduction

Recent THz studies of conductivity in bulk n-GaN have shown that dielectric response there can be well described by free carriers according to the Drude model [1]. In this work we demonstrate that in photoexcited $In_{0.2}Ga_{0.8}N$/GaN multiple quantum wells (MQWs), the photoconductivity can be described by a modified Drude model. The photoexcited carrier density decay rate is dominated by the restoration of the quantum-confined Stark effect (QCSE) [2], initially removed via a coherent dynamical screening effect (DSE) as a result of a strong femtosecond excitation [3].

II. Experiments and Results

Our samples consist of 10 InGaN MQWs, stacked between 7.2-nm thick GaN barriers. The quantum well (QW) width for 3 different samples are 1.8, 2.7, 3.6 nm. The QWs are subject to a strain-induced built-in piezoelectric field of 3.1 MV/cm. A detailed description of the samples can be found in Ref. [3]. To measure the carrier density decay, we use time-resolved THz spectroscopy. We use the output of an amplified Ti:sapphire laser, tuned around 800 nm to generate the probe terahertz pulses in a 1 mm thick ZnTe crystal by optical rectification. For THz detection, free-space electrooptic sampling in a 2 mm thick ZnTe crystal was used. The terahertz pulses are used to probe the conductivity dynamics of the InGaN/GaN MQWs. Another part of the Ti:sapphire output was frequency doubled to 400 nm and was used as a pump to photoexcite carriers only inside the InGaN QWs.

The photoexcited electrons and holes are, due to the built-in piezoelectric field, separated in space and hence induce a dipole moment with opposite polarity to that of built-in piezoelectric field. Thus every excited electron-hole pair will partly screen the built-in piezoelectric field. At large excitation fluences, the piezoelectric field can be completely screened [3], [4]. As the carriers recombine, the initial piezoelectric field will gradually restore. The change in electric field strength in the InGaN QWs will result in a change in the transition energy and optical transition probability in the QW due to the QCSE.

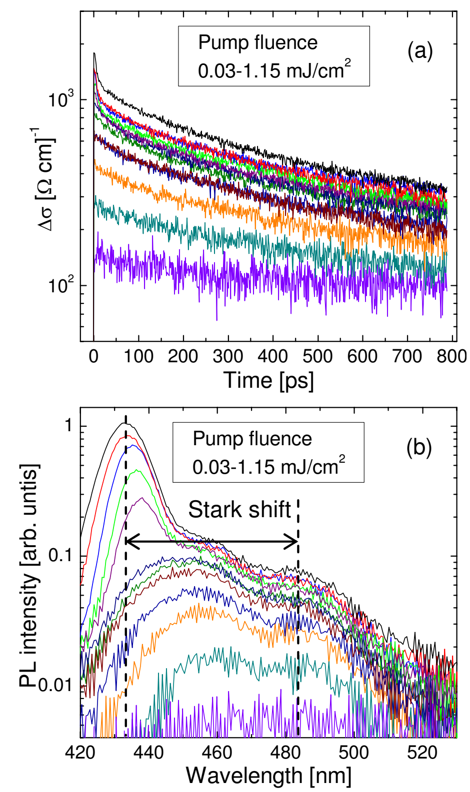

Fig. 1. (a) Measured change of the photoinduced conductivity of a terahertz probe as a function of pump delay time for pump fluences in the range 0.03-1.15 mJ/cm^2. (b) Measured time-integrated photoluminescence spectra for the same fluences.

Fig. 1(a) shows the photoinduced conductivity dynamics, obtained from 1D optical pump-THz probe measurements for the 1.8 nm-thick QWs for pump fluences in the range 0.03-1.15 mJ/cm^2. A nonexponential decay of the carrier density, due to dynamical restoration of the built-in piezoelectric field is observed, as the carriers recombine. At earlier times and large excitation fluence, the large overlap between electron and hole wavefunction in a screened quantum well results in a high recombination rate. As the carriers recombine, the restoration of the built-in piezoelectric field causes a decrease of the electron and hole wavefunction overlap and hence a slower recombination rate. The blue shift of the peak of the time-integrated photoluminescence (PL) spectrum, taken simultaneously with each pump-probe scan, shows the weakening and subsequently complete removal of the initially present strong QCSE, with increasing pump fluence (Fig. 1(b)) [3]. Recent time-resolved PL experiments on GaN/AlGaN QWs, where the piezoelectric field-induced QCSE is also present, have shown similar nonexponential decay dynamics [5].

Recently the coherent DSE was modeled [4], showing that the optical absorption coefficient, given by the instantaneous eigenenergies and overlap of the wavefunctions of electrons and holes, has a strong time dependence as the photoexcited carriers screen the built-in field. In order to accurately model the nonexponential decay observed here, an inverse problem must be solved, with recombination rate being a dynamic parameter. However one can estimate the carrier decay rate by the time it takes to decrease pump-induced THz conductivity by half. In Fig. 2 it is seen that at stronger pump, the carrier decay occurs faster because of enhanced recombination of the carriers due to tighter wavefunction overlap in a screened quantum well.

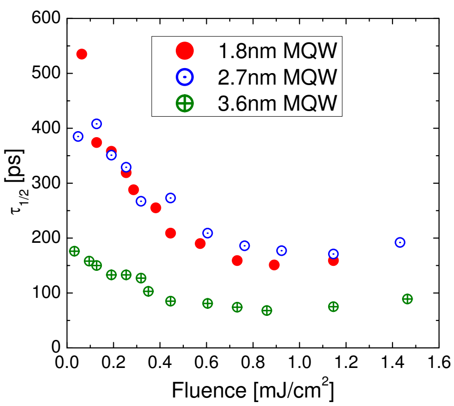

Fig. 2. Half-decay times for different fluences, for the three different quantum well thicknesses.

By time-resolving the probe THz pulse, we were able to measure the complex conductivity spectrum of photoexcited QWs at variable delays after optical excitation. The results for the sample with ten 1.8 nm-thick QWs for a pump-fluence of 0.17 mJ/cm^2, measured 5 ps after excitation are shown in Fig. 3. The conductivity spectrum differs from purely free carrier behavior, described by the Drude model. A classical generalization of the Drude model that can describe these deviations is the Drude-Smith model:

$$\sigma(\omega) = \frac{\epsilon_0 \omega_p^2 \tau}{1 - i\omega\tau}[1 + \sum_{j=1} \frac{c_j}{(1 - i\omega\tau)^j}]. \tag{1}$$

The first term is the Drude term, where ϵ_0 is the vacuum permittivity, ω_p is the plasma frequency and τ is the scattering time. The second term describes the persistence of the carrier initial velocity after a scattering event, where c_j describes the persistence of velocity for scattering event j. In practice only the first term of the sum is usually taken into account [6], [7]. The red lines in Fig. 3 are fits to the Drude-Smith model, where the real part, $\sigma 1$, and the imaginary part, $\sigma 2$, are fitted simultaneously with the same set of parameters. From these fits we obtain $\omega_p = 493 \pm 5$ THz, $\tau = 63 \pm 1.4$ fs and $c = -0.595 \pm 0.009$. The negative value of c indicates enhanced backscattering of carriers, which can be explained by the interface roughness, typical for InGaN/GaN MQWs.

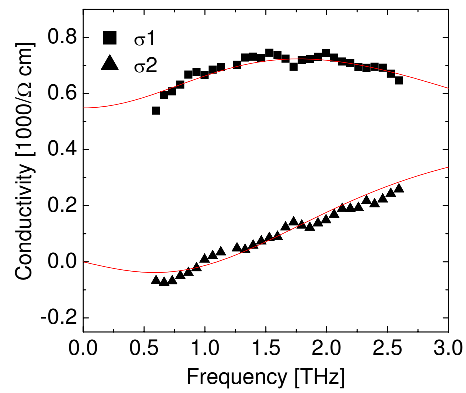

Fig. 3. Real ($\sigma 1$) and imaginary part ($\sigma 2$) of the conductivity at 5 ps delay after excitation with a fluence of 0.17 mJ/cm^2.

III. Conclusion

In conclusion, we have shown that the restoration of the built-in piezoelectric field in InGaN/GaN MQWs leads to a strongly nonexponential carrier density decay. The terahertz conductivity spectra are well fitted by the Drude-Smith model, showing an enhanced backscattering of carriers.

Acknowledgment

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