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Characteristics of THz carrier dynamics in GaN thin film and ZnO nanowires by temperature dependent terahertz time domain spectroscopy measurement

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ABSTRACT

We present a comprehensive study of the characteristics of carrier dynamics using temperature dependent terahertz time domain spectroscopy. By utilizing this technique in combination with numerical calculations, the complex refractive index, dielectric function, and conductivity of *n*-GaN, undoped ZnO NWs, and Al-doped ZnO NWs were obtained. The unique temperature dependent behaviors of major material parameters were studied at THz frequencies, including plasma frequency, relaxation time, carrier concentration and mobility. Frequency and temperature dependent carrier dynamics were subsequently analyzed in these materials through the use of the Drude and the Drude–Smith models.

1. Introduction

Terahertz time domain spectroscopy (THz-TDS) has been widely investigated for many applications in sensing and imaging technologies over the past two decades. Terahertz wave, with a frequency between 300 GHz and 10 THz, is especially attractive for various applications including security monitoring, biomedical imaging, high speed electronics and communications, and chemical and biological sensing. There is also an increasing interest for nondestructive testing using the THz waves because they have unique properties of propagation through certain media and cover a number of important frequencies. For such applications, THz-TDS has become a powerful tool and measurement technique that enables carrier dynamics at high frequencies to be characterized, and thus may lead to a better understand of the characteristics of high frequency optoelectronics and many other fundamental properties of materials. [1–5]

Using THz-TDS, one can determine frequency dependent basic properties of materials, including their complex dielectric constant, refractive index and electrical conductivity. Unlike conventional Fourier-Transform spectroscopy, THz-TDS is sensitive to both the amplitude and the phase, thereby allowing for a direct approach to determining complex values of material parameters with the advantage of high signal to noise ratio and coherent detection [6]. In addition, it is possible to carry out THz-TDS experiments without any electrical contact to the sample probed, which significantly simplifies electrical measurements of any type of nanostructures and nanomaterials. There have been a number of reports of dielectric properties of various materials probed by THz-TDS [7–9]. Among them, wide bandgap GaN and ZnO nanostructures are the most interesting materials to pursue because of their extensive applications in optoelectronic devices, photovoltaics, and high power electronic devices [10–14]. The high mobility and saturation drift velocity of GaN makes it one of potential materials for high power electronics that can operate beyond the gigahertz and reach to the terahertz frequency range [15–17]. ZnO nanowires (NWs) have been intensively used for many different types of sensors and recently for base structure for nanowire based photovoltaics [18]. For solar cell applications, it is critical to know the electrical properties of such nanowires as they would transport photogenerated carriers. THz-TDS measurement can be the most convenient and suitable method to determine such characteristics since electrical contacting to nanowires is almost not possible. Although many studies have been published on the electrical properties of GaN thin film and ZnO NW measured by THz-TDS, and only a few have investigated the temperature dependent THz-TDS measurements on bulk ZnO [19], there is no temperature dependent THz-TDS study of GaN or ZnO NWs.

Since temperature is an important factor in the operating conditions of any device, understanding its effect on carrier dynamics in constituent materials is a critical step in the optimization of high-frequency devices. In this work, we present a study of the temperature dependent carrier dynamics in GaN thin films and

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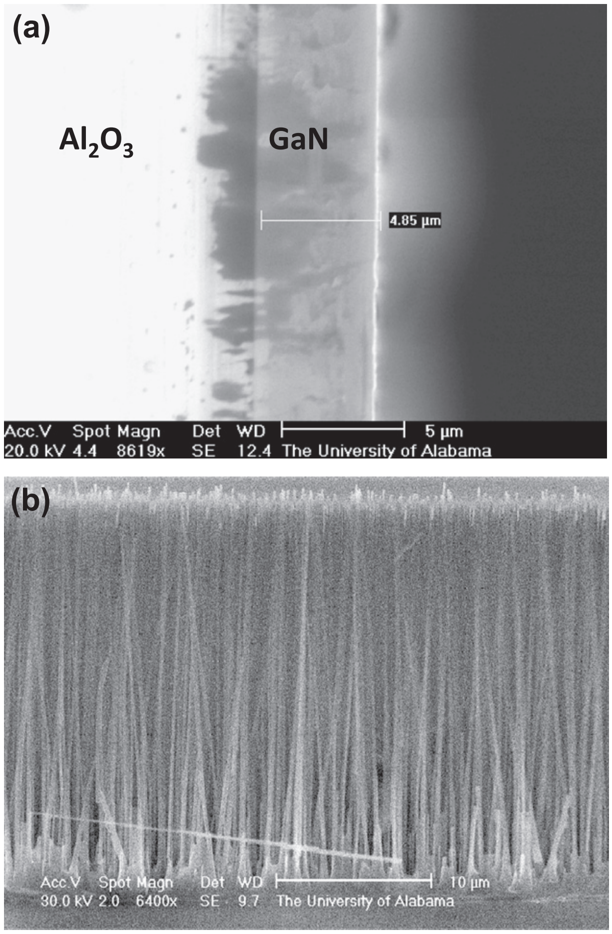

Fig. 1. SEM images of the Cross section of (a) GaN epilayer on sapphire substrate and (b) vertically aligned ZnO NWs.

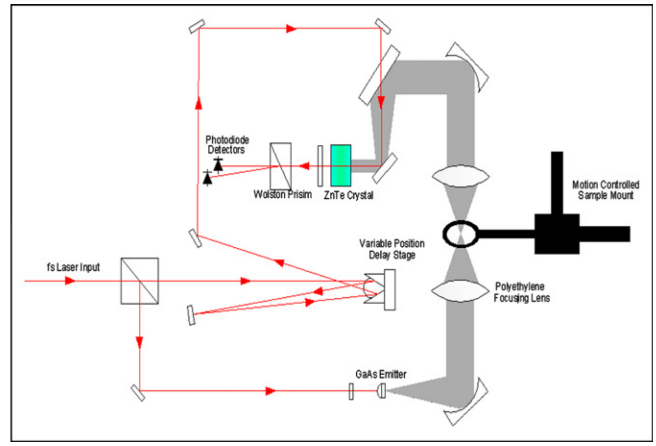

Fig. 2. Terahertz time domain spectrometer based on Ti:Sapp ultrafast laser at 790 nm. ZnTe is used for the detection and LT-GaAs photoconductive switch is used for emitter.

ZnO NWs obtained from THz-TDS measurements and extract important material properties in the THz.

2. Theoretical background

The theoretical approach and calculations have been discussed elsewhere [20]. Briefly, the THz wave propagation through the interface between two media and the relative field strength depend on both the complex reflection coefficient, $r_{12} = (n_1 - n_2)/(n_1 + n_2)$, and complex transmission coefficient, $t_{12} = 2n_1/(n_1 + n_2)$, at that interface. Let $S_o(\omega)$ be the complex amplitude of an incident THz wave propagating through a medium (e.g. air) indexed as 1. A reference configuration in our experiments consists of a THz wave passing through a substrate medium, indexed as 3, and whose amplitude is therefore given by: $S_{ref}(\omega) = t_{13} \times S_o(\omega) \times \exp(-i\,\omega\, d/c)$, where d is the thickness of the substrate medium, c is the speed of light. In a three medium configuration, when a thin film (indexed as 2) is between medium 1 and the substrate, by considering multiple reflections within the film, the amplitude of the THz wave can be represented by:

$$S_{sample}(\omega) = t_{12} \times t_{23} \times S_o(\omega) \times \exp(-i\omega\tilde{n}d/c)/[1 - r_{21}r_{23}(-i_2\tilde{n}\omega d/c)].$$

The complex spectral representation, $S(\omega)$, as a function of frequency can be obtained by Fast Fourier Transform (FFT) for each transmitted THz electric fields. The complex transmission coefficient $T(\omega)$, defined as the ratio of the transmitted signal $S_{sample}(\omega)$ through the sample (medium of interest) to reference signal $S_{ref}(\omega)$ (with only the substrate), can be written as:

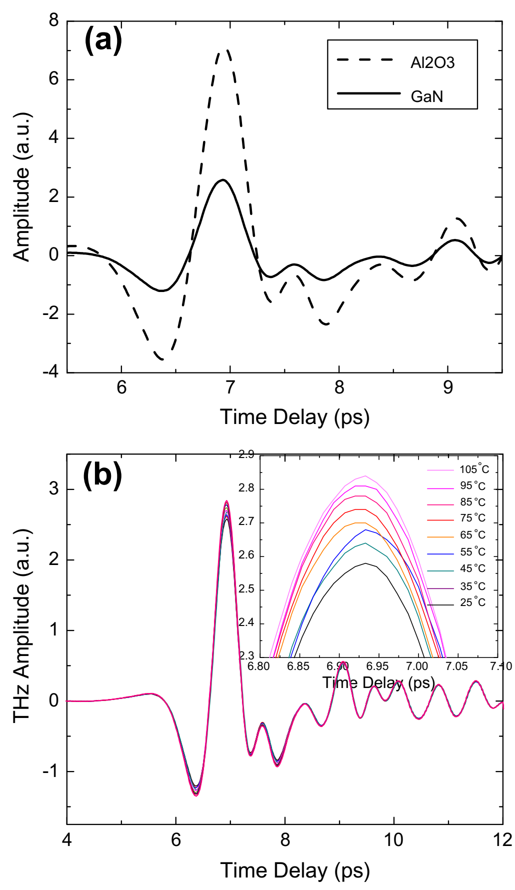

Fig. 3. (a) Measured THz responses transmitted through both the GaN thin film grown on sapphire substrate and the bare sapphire substrate for comparison and (b) temperature dependent measurement of GaN thin film with peak intensity changes with temperatures (inset).

$$T(\omega) = \frac{S_{sample}(\omega)}{S_{ref}(\omega)} = \frac{2\tilde{n}_s \cdot (\tilde{n}_r + 1) \cdot \exp(-i\omega(\tilde{n}_s - 1)d/c)}{(1 + \tilde{n}_s) \cdot (\tilde{n}_s + \tilde{n}_r) + (\tilde{n}_s - 1) \cdot (\tilde{n}_r - \tilde{n}_s) \cdot \exp(-2i\omega\tilde{n}_s d/c)} \quad (1)$$