Student Paper

Optical Parameters of $Zn_{1-x}Mg_xO$ Nanowires in THz Regime

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The terahertz (THz) dielectric constant, index of refraction, and conductivity of wurtzite $Zn_{1-x}Mg_xO$ nanowires (NWs) with Mg mole fraction of 9%, 18%, and 29% are determined using THz time domain spectroscopy (THz-TDS), a noncontact optical probe. The successful growth of $Zn_{1-x}Mg_xO$ with wurtzite structure permits the growth of double heterostructures and quantum well structures tailoring the bandgaps and thereby providing the optical and carrier confinement necessary in advanced light emitting diodes (LEDs) and laser diodes (LDs). In THz region, Zn-based material has a number of advantages in terms of device application, such as wide direct band gap, higher resistivity and transparency in a broad terahertz region. THz-TDS is a powerful tool to probe carrier dynamics at high frequencies, and thus may yield a better understanding of the characteristics of high frequency optoelectronics and many other fundamental properties of materials. It is sensitive to both the amplitude and the phase of the wave, thereby allowing a direct approach to determine complex values of material parameters with the advantage of high signal to noise ratio detection.

The THz-TDS system consisted of a commercial mode locked Ti:sapphire laser that produces 100 fs laser pulses with a repetition rate of 80 MHz. The fs laser beam is divided into two beams, one for exciting a photoconductive dipole antenna onto GaAs, and the other for measuring the THz signal at the detector crystal. The gap distance of the emitter antenna is 200 μm and is excited with a 7 mW of focused laser beam. The laser pulses generate free carriers in between the strip lines which are accelerated by an external bias voltage of 30 V (E_{bias} = 1.5 kV/cm). To increase the accuracy of the results, the THz bandwidth was limited to the range 0.3-2.2 THz where the systematic uncertainties associated with positioning error are minimized.

Fig.1 shows the experimental results of THz-TDS on Si (100), ZnO NWs, and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fractions. The photoexcited waveform of the Si wafer is treated as the reference. With higher Mg mole fraction, the delay time of the observed peak increases owing to increased dielectric constant impeding dipole relaxation. The negative dip in the plot is due to the fact that the THz pulse exists only for ~100 fs duration and the dipole tries to get back to steady state (capacitor) in the presence of the applied bias. The Fourier transformed spectrum of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with Mg mole fraction 9%, 18% and 29% are shown in Fig. 2. Comparison with similarly grown ZnO NWs reveals that Mg incorporation reduces the frequency of phonons. This could be attributed to the longer response delay with higher Mg mole fraction, as is evident from Fig. 1. Our experimental data suggests absorption dips at 2.08 THz and 2.2 THz for Si and $Zn_{1-x}Mg_xO$ NWs, respectively. The dips at 1.1THz, 1.7 THz and 1.9 THz are believed to be due to the water vapor absorption in the air. It is hard to determine the response for frequencies above 3 THz due to a lower signal to noise ratio. The index of refraction calculated from the Fourier transformed spectra is shown in Fig. 3. A higher refractive index is observed for $Zn_{1-x}Mg_xO$ NW samples with higher Mg mole fraction. This could be attributed to a larger phase change $\phi_{(\omega)}$ due to delay in the time domain for the higher Mg samples. Figs. 4 and 5 show the complex dielectric constants of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with Mg mole fraction 9%, 18% and 29%. In Fig. 4, the real part of the complex dielectric constant is observed proportional to the square of the refractive index ($n_{(\omega)}$). Dielectric constant relates the material's ability to conform to an electric field. Hence, we expect higher dielectric constant for materials with longer time delays, which is in accordance with our calculated results. Fig. 5 suggests that the imaginary part of the complex dielectric constant is proportional to the product of absorption ($\alpha_{(\omega)}$) or extinction (κ) coefficient and refractive index ($n_{(\omega)}$). Figs. 6 and 7 show

the real and imaginary parts of complex conductivity of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with various Mg mole fraction calculated using Drude-Smith model. With higher concentration of Mg, higher conductivity (real part) is observed due to a higher ε_1. Optical parameters of $Zn_{1-x}Mg_xO$ NWs extracted using THz-TDS technique outlined here will be useful in better understanding the carrier dynamics of high frequency optoelectronics since it probes the far-infrared region of the spectrum, which closely matches typical carrier scattering rates of 10^{12} to 10^{14} s^{-1} [1].

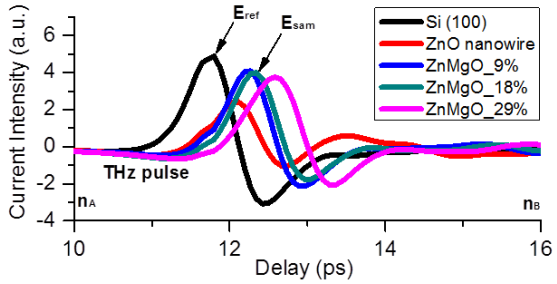

Fig. 1. Time domain THz waveforms with Si, ZnO NWs, and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fraction. The photoexcited waveform of Si is treated as reference.

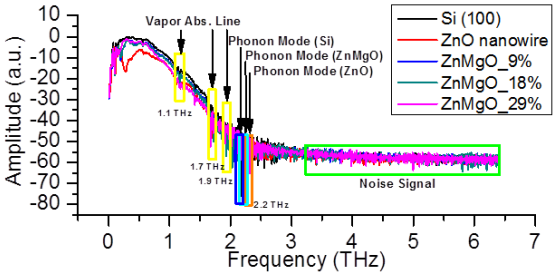

Fig. 2. Fourier transformed spectrum of Si, ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fraction.

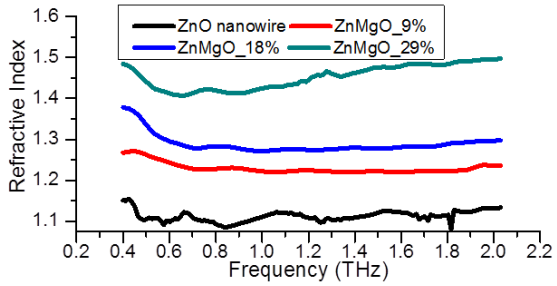

Fig. 3. Measured index of refraction of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fraction.

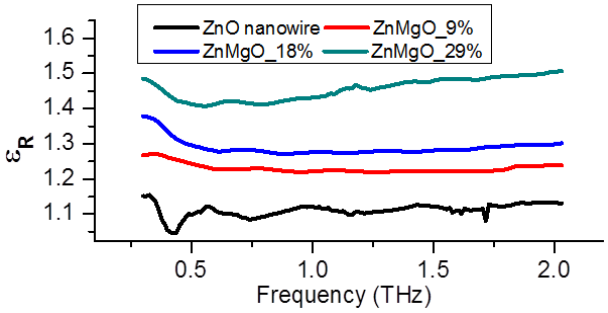

Fig. 4. Real part of complex permittivity of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fraction.

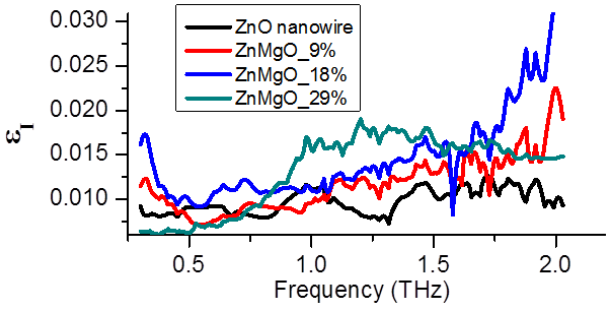

Fig. 5. Imaginary part of complex permittivity of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fraction.

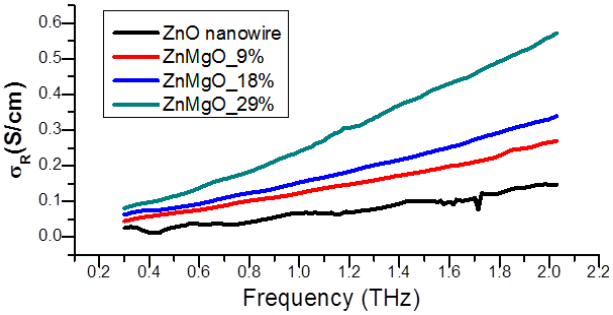

Fig. 6. Real part of complex conductivity of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fraction.

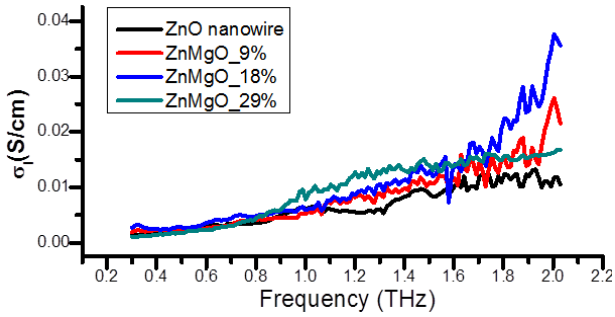

Fig. 7. Imaginary part of complex conductivity of ZnO NWs and $Zn_{1-x}Mg_xO$ NWs with varying Mg mole fraction.

References

[1] J. Baxter and C. Schmuttenmaer, "Conductivity of ZnO Nanowires, Nanoparticles, and Thin Films Using Time-Resolved Terahertz Spectroscopy," *J. Phys. Chem. B* **2006,** *110,* 25229-25239. (Journal Article)