Localized Surface Phonon Polariton Resonators in GaN

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Abstract: GaN micro-disk resonator arrays were fabricated and measured within the *Restrahalen* band of GaN. Far-IR spectroscopy shows evidence for localized surface phonon polariton resonances, results which are confirmed by finite-element models of the fabricated structures.

OCIS codes: (240.6680) Surface plasmons; (230.5750) Resonators

1. Introduction

Interest in the field of plasmonics has grown significantly because of the potential for novel nanophotonic devices. In plasmonics, highly desired optical phenomena, including subwavelength mode confinement and electric field enhancement, are enabled by the interaction of light with collective charge oscillations, or plasma oscillations[1]. The plasma oscillations strongly influence the optical response of the material, and beyond a certain wavelength, the real part of the material's permittivity becomes negative. This negative response is required for plasmonic applications. Additionally, the imaginary part of the permittivity is related to optical loss, and for most applications it is desired that this be very small.

Due to the coherent oscillation of atoms in a polar unit cell, polar semiconductors also exhibit a negative permittivity in the frequency range between the transverse optical (TO) and longitudinal optical (LO) phonon frequencies, a wavelength range typically referred to as the *Restrahalen* band. *Phononics*—similar to plasmonics—is governed by the dynamics of phonons instead of collective charge oscillations. This is particularly important when considering optical loss because optical phonon lifetimes can be significantly longer than scattering times in metals or doped semiconductors[2]. Ultimately, lower loss enables subwavelength resonators with larger quality factors, improved propagation of surface phonon polaritons (light coupled to phonons on the surface of polar semiconductors), and other desirable behavior.

In this work, we demonstrate subwavelength resonators that operate in the *Restrahalen* band of GaN. The advantages of GaN compared to other polar material systems are that the material can be grown epitaxially, III-nitride materials can be fabricated using well-established semiconductor processing techniques, and GaN can be grown on a number of substrates, including SiC, which behaves as a low-loss dielectric in the GaN *Restrahalen* band.

2. Methods and Results

Undoped GaN samples were grown on the Si-face of double-side polished SiC substrates using plasma assisted molecular beam epitaxy. The thickness of the GaN was measured using a cross-section scanning electron

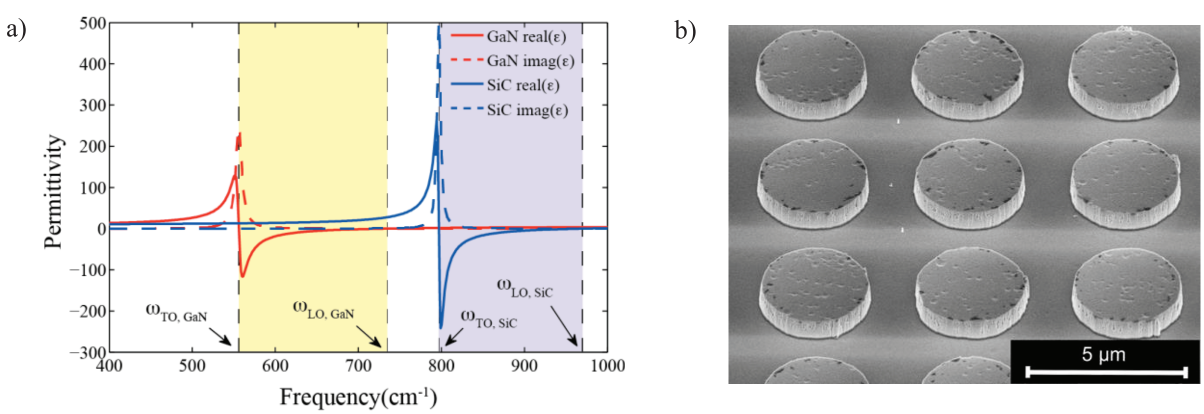

Fig. 1. a) Real (solid) and imaginary (dashed) part of the dielectric function of GaN (red) and SiC (blue). The yellow and blue shaded areas correspond to the *Restrahalen* bands for GaN and SiC, respectively. b) Tileted SEM image of the fabricated microdisk array.

microscope (SEM) and determined as 675 nm. Angle-dependent reflection measurements of the unpatterned GaN samples were used with an isotropic Lorentzian model to determine the permittivity of both the GaN epitaxial layer and the SiC substrate [3, 4]. The TO and LO phonon frequencies for the sample were determined to be 556 and 735 cm^{-1}, respectively. Figure 1a depicts the real and imaginary part of the permittivity for both materials.

A 0.5x0.5 cm^2 array of disks with a diameter of 3.2 μm and a period of 4.8 μm arranged in a square lattice were fabricated using standard processing techniques. Optical lithography was used to define an array of holes and a nickel etch mask was deposited using electron beam evaporation. The GaN was etched to the SiC substrate using an inductively coupled plasma reactive ion etch. Finally, the nickel mask was removed using a standard wet etch. Figure 1b shows a tilted image of the disk array obtained using SEM. The uniformity of the pillar diameter and spacing was better than 5% over the entire fabricated area. The array of microdisks was characterized using angle- and polarization-dependent reflection measurements in a vacuum Fourier Transform infrared spectrometer (FTIR). Reflection from the microdisk array was normalized to the reflection from a gold mirror for the same incident angle

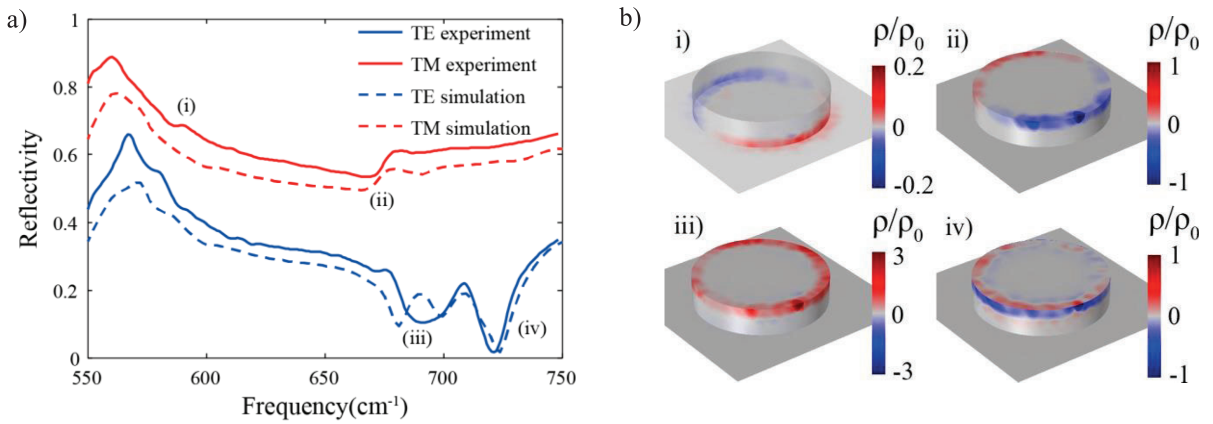

Fig. 2. a) Experimental and simulation results of reflectivity of the GaN microdisk array. The incident angle of the polarized light is 45°. b) Plots of charge density of four different oscillation modes observed in 3D simulation: i) transverse dipole (TD) for TE light at 603 cm^{-1}; ii) TD for TE light at 673 cm^{-1}; iii) hybrid mode for TM light composed of TD and a vertical dipole (VD) at 693 cm^{-1}; and iv) hybrid mode for TM light composed of quadrupole and VD at 721 cm^{-1}. Features in the reflection spectra from these modes are indicated in Fig. 2a.

and polarization. Figure 2a depicts the spectral response for the transverse magnetic (TM) and transverse electric (TE) polarizations at an incident angle of 45°. The patterned sample was also simulated with a full 3D model using the finite element software COMSOL Multiphysics with material parameters that were recovered from the initial characterization of the unpatterned sample and SEM images. The numerical simulations are plotted with the experimental data in Fig. 2a; there is excellent agreement between experiment and the numerical model.

The dips and steps in the spectral response of the reflection data are associated with various localized optical modes in the GaN microdisks. The localized modes were identified using the calculated charge density in the finite element model. Figure 2b shows the charge density for four separate modes that are also identified on the measured reflection spectra. The two TE modes are clearly identified as (i) transverse dipole (TD) at the base of the microdisk, (ii) TD at the top of the microdisk. In order to identify the TM modes, numerical calculation was done for both small and large incident angles. For small incident angles, mode (iii) is also a TD and mode (iv) is a quadrupole. For larger incident angles, as shown in the figure, a vertical dipole component is introduced into the system. Therefore we identify them as (iii) hybrid mode of TD and vertical dipole (VD), (iv) hybrid mode of quadrupole and VD. Moreover, the charge density of different modes varies according to the mode strength shown in the spectra.

4. Conclusion

We demonstrated localized phonon polariton modes in subwavelength GaN microdisks arrays. The results represent a promising path to realizing low-loss phononic devices in the mid-infrared and serve as a launching point for new quantum phononic devices that incorporate the interaction between intersubband transitions and phonon polaritons.

4. References

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