Mid-Infrared Doping-Tunable Extraordinary Transmission from Sub-Wavelength Gratings

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Motivation—It has been known for some time that metallic gratings formed on dielectrics can exhibit unique transmission properties. More recently, Ebbessen et al., studied such structures and demonstrated the phenomenon of extraordinary transmission (ET), where, at certain wavelengths, more light passes through the sample than predicted by aperture theory. This effect has been ascribed to surface plasmon (SP) enhancement of the transmission process. There has been significant interest in utilizing such structures for a variety of photonic devices, the majority of which are designed to function in the visible and near-IR.

Accomplishment—We have demonstrated doping tunable extraordinary transmission from sub-wavelength apertures in a periodic two-dimensional metallic grating deposited upon n-doped GaAs. A general expression for the SP resonance condition is given by:

$$\lambda = a_0\sqrt{\frac{\varepsilon_s\varepsilon_m}{\varepsilon_s+\varepsilon_m}} \approx a_0\sqrt{\varepsilon_s} \text{ for } |\varepsilon_m| >> |\varepsilon_s| \quad (1)$$

Here, λ is the free space wavelength, a_o is the grating period, ε_s is the real part of the dielectric constant of the semiconductor, and ε_m is the real part of the dielectric constant of the metal. For commonly used metals in the mid-IR, the condition $|\varepsilon_m|>>|\varepsilon_s|$ holds, allowing the approximation to be used. A typical grating structure is shown inset in Fig. 1.

The free electrons in bulk semiconductors can exhibit well known collective charge oscillations, or plasmons, where the natural resonance frequency (ω_p) is directly proportional to the carrier concentration. For semiconductors the background dielectric function can be tuned by varying the free-carrier density. Neglecting scattering, the frequency dependent effects of free-carriers can be incorporated into the dielectric function of the semiconductor using:

$$\varepsilon(\omega) = \varepsilon_s\left(1-\omega_p^2/\omega^2\right) \quad (2)$$

Figure 1 displays the frequency dependent dielectric function for various doping concentrations in GaAs. A vertical line drawn on Fig. 1 at a wavelength of 8 µm (the design wavelength for the structures studied in this work) shows the large dielectric contrast obtained as the carrier concentration varies by more than an order of magnitude. By coupling the ET and the doping tunable dielectric function we have demonstrated wavelength tunability in the mid-infrared of ~23 cm^{-1}, or approximately 0.15µm, around the 8 µm design wavelength. We have achieved transmission peaks as narrow as 17 cm^{-1}.

Significance—The tunablity and narrow linewidth of the transmission peaks suggests that such gratings could be used in external cavity structures for Quantum Cascade laser systems. Such systems would have applications in chemical and biological sensing. The sensitivity of the device to the carrier density suggests that electrically tunable grating structures should be possible, enabling tunable filters or modulators for mid-infrared applications. Surface plasmon gratings also have the potential for amplifying chemical IR signatures as molecules adsorb onto metal surfaces.

Sponsors for various phases of this work include: Laboratory Directed Research & Development

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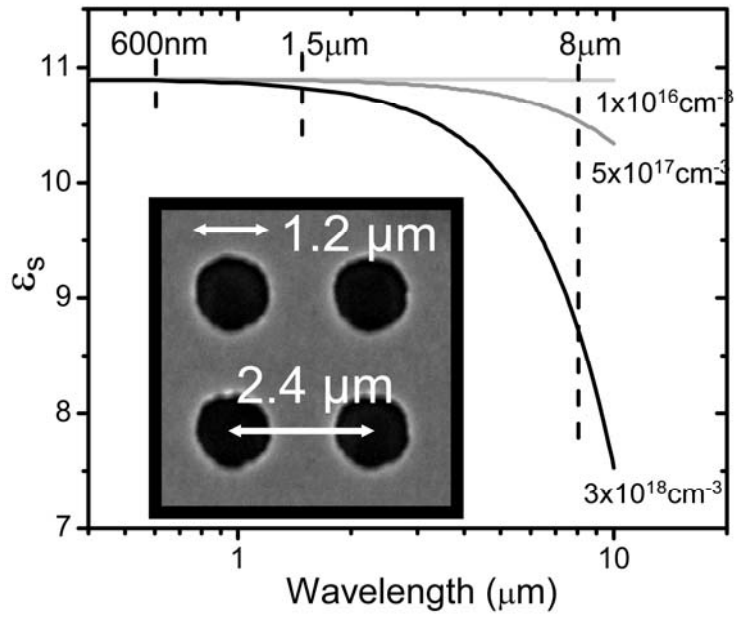

Figure 1. The dielectric function of GaAs has large free-carrier variation in the mid-infrared. Inset: Scanning electron micrograph of an extraordinary transmission grating structure. The grating period is 2.4 μm, and the individual hole diameters are 1.2 μm.

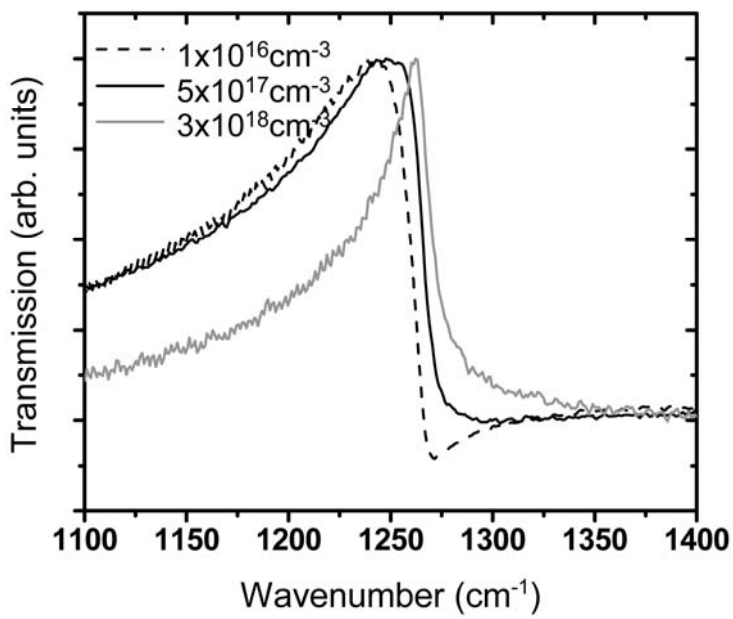

Figure 2. Unpolarized transmission spectra for all three samples at normal incidence. The transmission peaks show a distinct shift as the doping of the epitaxial layer increases.