BAPVC Annual Project Report

Project Title: Nanostructured metallic films as both broadband antireflective coatings and transparent electrodes for semiconductor devices

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Summary:
Nanostructured metallic films have emerged as potential replacement for metal oxide films as transparent electrodes in optoelectronic devices. An ideal transparent electrode should possess a high, broadband transmittance, regardless of the underlying semiconductor. Many metallic transparent electrodes are highly transmissive on glass, however, when integrated on a high index substrate, an additional anti-reflective (AR) layer such as silicon nitride is required to maintain high broadband transmissivity. Under the BAPVC program, the Brongersma group has demonstrated that optimized nanostructured metallic films with deep subwavelength structural features can behave as transparent dielectrics and thus be used as an AR coating (Fig. 1). In this role they feature a dual functionality both as an anti-reflective layer and a transparent electrode layer. Compared to previously proposed metallic electrodes, the demonstrated electrode feature a high broadband transmittance and low reflectance while preserving a high sheet conductivity (Fig. 2,3,4), a small dependence on incident angle (Fig. 5), and a design that can be easily tailored to the target low or high index semiconductor for optimal performance. This electrode technology eliminates the need for an additional dielectric anti-reflective layer reducing one material and one processing step.

Key Accomplishments:

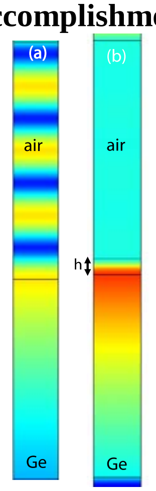

Figure. 1. **A nanostructured metallic electrode with deep subwavelength structural features resembles an artificial dielectric** (a) Magnetic field distribution shows high reflection of the incident light by a high index semiconductor such as Ge (λ = 1.3 μm). Reflection suppression and transmission enhancement (b) by a quarter wavelength thick dielectric layer (c) by an optimized deep subwavelength Ag grating (TM polarization).

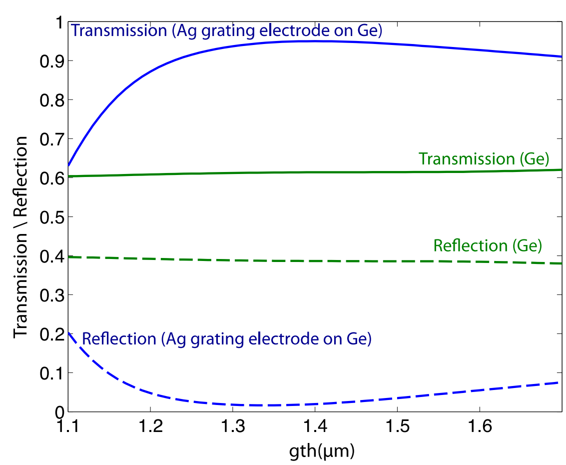

Figure. 2. **A subwavelength Ag grating electrode on Ge provides broadband transmission enhancement and reflection suppression while maintaining a high sheet conductivity.** The green and blue curves correspond to the geometries presented in Fig. 1 (a) and (c), respectively. Sheet resistivity of the Ag electrode is 0.12 Ω/sq.

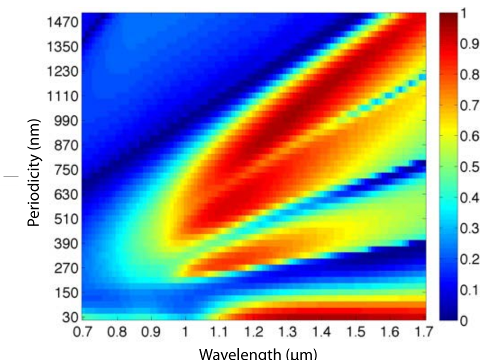

Figure. 3. **Transmission map for Ag grating electrodes with constant sheet conductivity on Ge shows electrodes with deep subwavelength structures provide the most broadband optical properties.** Sheet resistivity of all Ag gratings is 0.12 Ω/sq and Ag thickness is 193 nm.

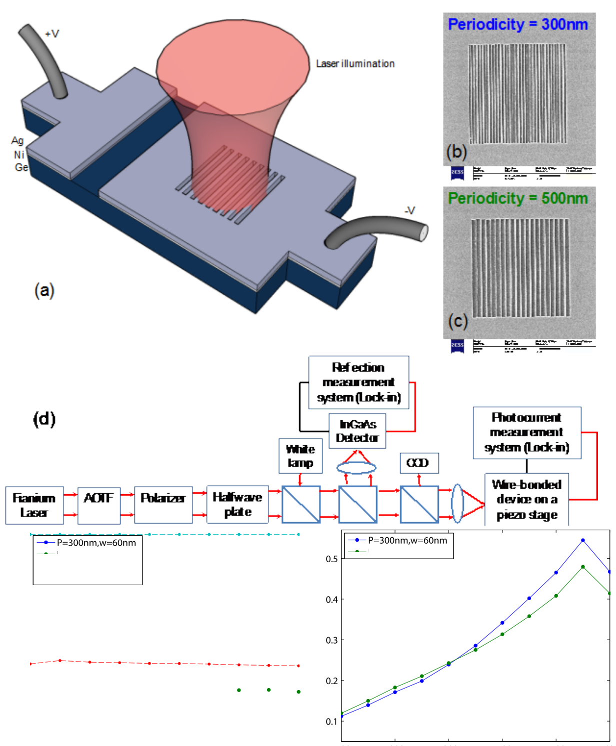

Figure. 4. **Optical reflection and photocurrent measurements confirm broadband high reflection suppression for nanostructured Ag electrodes.** (a) A schematic of the measurement platform where an electrode of a planar Ag-Ge-Ag Schottky detector is patterned with a grating geometry. The electrode transmits light into Ge where it generates electron-hole pairs that are extracted as photocurrent. (b, c) SEM images of Ag grating electrodes made with Neon ion beam milling with periodicity = 300 nm and periodicity = 500 nm (d) Photocurrent and reflection measurement setup for polarization and spectrally resolved measurements (e) Reflection measurements for Ag, Ge, and Ag grating electrodes with different periodicities on Ge (TM polarization) (e) Photocurrent measurements for Ag electrodes on Ge (TM polarization).

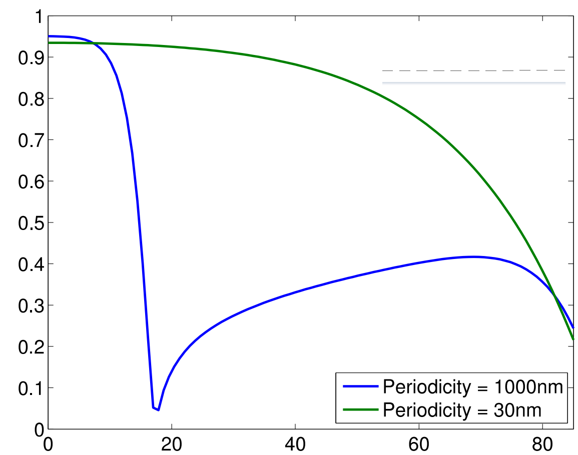

Figure. 5. **Transmission through a deep subwavelength Ag electrode has a small dependence on the incident angle.** The green and blue curves correspond to transmission of Ag gratings on Ge with periodicities of 30 nm and 1000nm. The sheet resistivity for both Ag electrodes is 0.12 Ω/sq.

Future Work:

The Brongersma group is currently developing polarization independent antireflective transparent electrodes over various semiconductor substrates. Althought a demonstration in the infrared spectral range was easiest, they are now also exploring the possibility to operate over the entire visible and infrared spectrum. If successful, this work will obviate the need for an additional dielectric antireflective layer. This work is expected to provide a significant cost reduction in the fabrication of conductive transparent electrodes based on the low cost of metals versus conventional transparent electrodes based on transparent oxides.