Metallic Nanoconcentrator for a Lateral Nanowire Multijunction Photovoltaic Cell

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Introduction

Subwavelength metallic nanotubes are used to spectrally filter and concentrate light into localized hotspots through the excitation of dipole-like surface plasmon (SP) polarization modes. At SP resonance, the free electrons in the antenna collectively and coherently oscillate in the same direction, creating an electromagnetic field in the near-field. It is this near-field resonance that allows for localized and non-radiative energy transfer to a material or substance located inside the near-field of the antenna.

The geometry we simulated using Finite-Difference Time-Domain modeling consists of an Ag ring resonator with a nanowire positioned inside the ring and a geometrically similar nanowire placed just outside of the ring as shown in the figure below. The motivation behind the placement of the nanowires both inside and outside the ring was to locate them in regions of maximum field enhancement to maximize the amount of energy absorbed by the semiconductor material at plasmonic resonance. In the case of the second nanowire, placing it just outside the ring will demonstrate enhanced absorption to both a different spatial and spectral region since the LSP resonance of the ring is expected to shift on increasing the diameter and reduce the field enhancement just outside the ring perimeter along the direction of electric-field-polarization.

Design of Lateral Nanoconcentrator

The plasmonic modes of a nanowire can be spectrally selective. The dotted line shows a fixed absorption in the AlGaAs nanowire at resonance when the LSP mode of the ring is excited. The solid line representing the GaAs nanowire shows a much stronger enhancement of 380% at around where the symmetric bonding mode occurs. The electromagnetic field magnitude (E) profile across the x-z plane midway through the nanowires and ring antenna at the symmetric bonding (left) and LSP (right) resonance modes are also presented.

Plasmonic Modes of Nanoring Antenna

A ring resonator antenna was selected for spectral splitting and electromagnetic concentration because the antenna structure maintains the ability to focus the electric field along the ring and nanowire axis such that it is locally and uniformly enhanced within the ring cavity when resonance occurs. Coupling and interaction between the inner and outer surfaces result in dipolar excitations with energy levels that can generally be categorized into a two-level dipolar symmetric bonding mode and a higher energy dipole-antisymmetric bonding mode. As the plasmon losses between the inner and outer surfaces increases, the splitting between these hybridized modes increases. The rings are thus able to red-shift peaks to lower energies and achieve a better tuning range without increasing the size of the geometry thereby reducing the thickness of the ring. This reduces the material losses, retardation effects and radiation damping associated with larger nanorings.

Within the dipole limit, the polarization pattern of the symmetric bonding mode at resonance leads to a strong dipolar excitation that is not observable in terms of geometric concentration in the ring cavity. The anti-symmetric bonding mode is far weaker and only occurs at wavelengths too short to have the bulk of energy in the visible region of the solar spectrum but we show that this SP mode can be excited near the material resonance of the metallic nanotubes. This localized surface plasmon (LSP) mode is less dependent on the thickening than the ring axis since it does not originate from coupling between the disc and cavity modes and so can be tuned independently.

Since its relatively higher bandgap energy will benefit from the LSP resonance. Placing a nanowire just outside the ring also allows for better outcoupling of the energy from the LSP mode. The ring induces a dipole in the AlGaAs nanowire and redirects the energy from the near-field enhancement so that it tunnels through into the nanowire, thereby increasing the absorption efficiency of the semiconductor.

The inner diameter is kept constant at 40nm while increasing the outer radius. As the thickness-to-diameter ratio decreases, coupling between the ring and material increases gaining plasmonic enhancement. The symmetric bonding mode becomes increasingly red-shifted. The LSP resonance does not noticeably shift since it is primarily dependent on the material resonance of the Ag ring. In addition to a redshift in the bonding resonance of the LSP regime, the decrease in the thickness to diameter ratio also results in a reduced level of confinement for both SP and LSP resonance peaks. These trends illustrate the tradeoff between a thicker and thinner ring. In the latter cases, there is more mode splitting and tunability due to an increased mode coupling but the field enhancement is no longer as strong, potentially increasing the amount of material loss in the antenna itself. Confinement in a thin enough ring eventually results in quenching of the LSP mode with no coupling.

The plots below demonstrate the effect of periodic boundary conditions. The reduced thickness of the ring results in energies normally resulting from periodicity is only observed for the outer ring peak wavelength and a shoulder peak resulting from the ring’s bonding mode. This suggests that the interaction between the inner and outer rings is perturbed, further influencing the symmetric bonding mode of the ring geometry. Although geometrically similar, the NBR resonance and so compromises the large absorption enhancement in the internal GaAs nanowire that was gained with just a single geometry.

Plasmonic modes of a nanoring antenna include (a) symmetric bonding, (b) antisymmetric bonding, (c) symmetric coupling, and (d) antisymmetric coupling. The radii and thickness of the nanorings are 40nm and 10nm, respectively.