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Leaky-mode effects in plasmonic-coupled quantum dot infrared photodetectors

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The effects of a heavily doped GaAs top contact layer on a plasmonics-integrated InAs quantum dot infrared photodetector (QDIP) are investigated. A metal photonic crystal (MPC), a 100 nm-thick gold film perforated with a 2.5 μm-period, 2-dimensional square hole array, is employed as a plasmonic coupler. The MPC is fabricated on QDIPs with identical structures except for the thickness (0.1 and 1.3 μm) of the top contact layer (doping concentration ~2 × 10^{18} cm^{-3}). For the lowest order surface plasma wave (SPW) resonance, the resonance wavelength undergoes a blue shift of 0.27 μm from 8.26 μm, and the responsivity and detectivity drop by ~50% for the thicker contact layer. These effects are explained by leaky mode characteristics resulting from the free-carrier-reduced dielectric constant in the contact region that impacts the SPW resonance.


Several groups have reported absorption enhancement of infrared (IR) detectors such as InAs quantum dot IR photodetectors (QDIPs) using surface plasma wave (SPW) coupling structures. A metal film perforated with a 2-dimensional (2D) hole array, referred to as a metal photonic crystal (MPC), often has been used as the plasmonic coupler. For the case of a homogenous semiconductor below an MPC of period p, the SPW wavelength excited at the MPC/semiconductor interface at normal incidence, λ_{ij}, and the SPW field penetration depth into the semiconductor, δ_{ij}, are given approximately by

\[ \lambda_{ij} \approx p\sqrt{\varepsilon_d/\left(\varepsilon_i^2 + p^2\right)}, \quad \delta_{ij} \sim \left(\lambda_{ij}/2\pi\right)\sqrt{\text{Re}(\varepsilon_m)/\varepsilon_d}, \] (1)

where i, j correspond to the orders of the 2D wavevector of the MPC square hole array, \varepsilon_m and \varepsilon_d are the dielectric constants of the metal and semiconductor at \lambda_{ij}, with |\varepsilon_m| \gg |\varepsilon_d| for mid- and long-wave IR ranges. Generally, the discussions of the SPW coupling have made the simplifying assumption of treating the semiconductor as a semi-infinitely thick homogenous material. However, detectors require a layer structure with a heavily doped ohmic contact layer atop an absorber. At IR wavelengths, the free-carrier (~2 × 10^{18} cm^{-3}) contribution to the dielectric response of the contact layer lowers the refractive index [Δ(√\varepsilon_d) ~ -0.23 relative to the undoped QD stack at \lambda_{ij} ~ 8 μm] forming an antiguiding structure. The effects of this structure on the SPW excitation at an MPC/doped semiconductor interface have been observed through a blue shift of the λ_{ij}. Here, we demonstrate that the antiguiding structure directly impacts the photosponse, even though the contact layer thickness, t, is well within δ_{01}. This is a result of leaky wave antenna effects that enhance the coupling of the SPWs into substrate radiation, thereby reducing their coupling to the absorber. A reduction in coupling is critical in the
schematically illustrated in Fig. 1. An identical MPC, perforated with a 2D hole array having \( p \sim 2.5 \mu m \) and a hole diameter of \( \sim 1.2 \mu m \) was processed atop each MPC device. A 100 nm-thick gold film was used for the MPCs which fully covered the 300-\( \mu m \)-diameter aperture on the top surface of each \( 410 \times 410 \mu m^2 \) mesa device. For convenience, the two MPC devices are referred to as the \( t_{0.1} \)- and \( t_{1.3} \)-MPC devices. Likewise, the two bare devices, having the same 300-\( \mu m \)-diameter open aperture but without the MPC, are denoted as \( t_{0.1} \)- and \( t_{1.3} \)-bare devices. The photoresponse was characterized with normal incidence at 77 K using a Fourier transform IR spectrometer and an 800 K blackbody source.

Figure 2(a) shows the spectral response curves of the four devices at a bias of 3.2 V where the detectivity, \( D^* \), of the MPC devices is largest. Both \( t_{1.3} \)- and \( t_{0.1} \)-bare devices have photoresponse spectra very similar to previous reports with broad peaks at \( \sim 5.5 \) and 9.0 \( \mu m \), identified as QD-to-continuum and QD-to-quantum-well transitions.\(^{3,12}\) The peak responsivities, \( R_p \) peak responsivities, \( 100 \) nm-thick gold film was used for the MPCs which fully covered the 300-\( \mu m \)-diameter aperture on the top surface of each \( 410 \times 410 \mu m^2 \) mesa device. For convenience, the two MPC devices are referred to as the \( t_{0.1} \)- and \( t_{1.3} \)-MPC devices. Likewise, the two bare devices, having the same 300-\( \mu m \)-diameter open aperture but without the MPC, are denoted as \( t_{0.1} \)- and \( t_{1.3} \)-bare devices. The photoresponse was characterized with normal incidence at 77 K using a Fourier transform IR spectrometer and an 800 K blackbody source.

The thickness difference results in shifts of the SPW resonance wavelengths, \( \lambda_{01} \sim \rho \sqrt{\delta_e} \), \( \lambda_{11} \sim \lambda_{01}/\sqrt{2} \), and \( \lambda_{02} \sim \lambda_{01}/2 \) from Eq. (1). The thickness difference results in shifts of the SPW wavelengths of \( \Delta \lambda_{01} \), \( \Delta \lambda_{11} \), and \( \Delta \lambda_{02} = 0.27 \), 0.10, and 0.06 \( \mu m \) for \( \Delta \lambda_{01} = \lambda_{01}(t_{0.1}) - \lambda_{01}(t_{1.3}) \). In addition, \( R_p \) is decreased for the thicker contact layer device as seen in Fig. 2(a) and Table I. The peak \( R_p \)'s for \( t_{0.1} \)-MPC are considerably greater than those of the \( t_{1.3} \)-MPC device. This is most prominent for \( \lambda_{01} \) where the \( t_{0.1} \)-MPC device has a peak intensity \( \sim 3.5 \times \) larger than the \( t_{1.3} \)-MPC device. These \( R_p \)'s correspond to \( \sim 1 \times 10^8 \) and \( \sim 4 \times 10^7 \) that of the bare devices.

The \( n^2 \)-GaAs layer has a bulk plasma contribution to the dielectric constant, \( \varepsilon_p \), by \( \varepsilon_p = \varepsilon_{GaAs}(1 - \omega_p^2/\omega^2) \), where \( \omega_p \) is the plasma frequency defined by \( \omega_p^2 = 4 \pi n_e e^2/\varepsilon_{GaAs} m_e^* \), with \( n_e \), \( e \), \( \varepsilon_{GaAs} \), and \( m_e^* \) the free carrier density \( (-2 \times 10^{18} \text{ cm}^{-3}) \), the electron charge, the high frequency dielectric constant of undoped GaAs, and the GaAs electron effective mass.\(^8\) The absorption associated with the free carriers (the imaginary part of \( \varepsilon_p \)) is insignificant in this work and is not considered in \( \varepsilon_p \).\(^13\) A rigorous coupled-wave analysis (RCWA) was carried out for the simulation of absorption by SPWs with \( \varepsilon_p \) that decreases with increasing wavelength in the inset of Fig. 2(b). The structure employed in the simulation is shown in Fig. 1. It consists of a \( p = 2.5 \mu m \), 100 nm-thick Au MPC as in the experiment, a doped GaAs \( (t = 0.1-1.5 \mu m \) with the given \( n_e \) \( \mu m \) top contact layer, a QD stack, and a semi-infinite GaAs substrate. From the compositional and doping average, the QD stack was replaced by a homogeneous, undoped \( Ga_{0.09}Ga_{0.91} \)As layer with a dielectric constant very close to \( \varepsilon_{GaAs} \). A Drude model was used for the dielectric constant of the MPC Au film.\(^4^4\)

\[ \text{TABLE I. Summary of experiment and simulation.} \]

<table>
<thead>
<tr>
<th>( \lambda_{01} )-MPC</th>
<th>( \lambda_{1.3} )-MPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_p ) (bare) [mA/W]</td>
<td>44.8 (3.7)</td>
</tr>
<tr>
<td>( D^* ) (bare) ( \times 10^9 \text{ cmHz}^{-1/2}/\text{W} )</td>
<td>7.8 (0.60)</td>
</tr>
<tr>
<td>( \lambda_{01} ) (bare) [\mu m]</td>
<td>8.26 (8.204)</td>
</tr>
<tr>
<td>( \lambda_{11} ) (bare) [\mu m]</td>
<td>5.76 (5.794)</td>
</tr>
<tr>
<td>( \lambda_{02} ) (bare) [\mu m]</td>
<td>4.15 (4.073)</td>
</tr>
</tbody>
</table>

FIG. 2. (Color online) (a) 77 K photoresponse spectra of the four QDIPs shown in Fig. 1. Inset: A plot of peak shift vs SPW resonance wavelength from the experimental data (this figure) and the simulation results from (b). Here \( \delta_x \) in x-axis means \( \delta_x \) and \( \delta_y \) at \( t = 1.3 \mu m \). (b) A plot of absorption versus wavelength for \( t = 0.1 \) and 1.3 \( \mu m \) structure calculated by RCWA. Inset: A plot of \( \varepsilon_p \) vs \( \lambda \). A dashed line indicates \( \varepsilon_{GaAs} \).
8.14 μm. As t increases further, the peak decreases and broadens with another peak that begins to form at 7.98 μm for t = 1.2 μm. Also, λ_{01,th} gradually moves to and reaches 7.92 μm, and as seen in Fig. 3 and its inset, the peak absorption slightly increases to 0.04 as t approaches 1.5 μm. Absorption recovers somewhat with increasing t beyond 1.5 μm but will be effected by free-carrier absorption as t → ∞ (not shown).

From the comparison of Fig. 2(a) with Figs. 2(b) and 3, the peak around 8.2 μm for t ≲ 0.5 μm in the simulation is identified as the first SPW resonance of the t_{0.1}-MPC device in Fig. 2(a) while the weak, broad peak around 7.9 μm for t ≳ 1.1 μm is the corresponding peak for the t_{1.3}-MPC device. The peaks at λ_{11,th} and λ_{02,th} of each spectrum in Fig. 2(b) have similar correspondence to Fig. 2(a). All λ_{ij}'s and λ_{ij,th}'s for t = 0.1 and 1.3 μm are summarized in Table I. The inset of Fig. 2(a) is a plot of Δλ_{ij} and Δλ_{ij,th} versus λ_{ij} (t_{1.1}). In the inset, Δλ_{ij,th} increases with wavelength, as expected from ε, and shows a similar trend to Δλ_{ij}. While Δλ_{01,th} = 0.29 μm fairly close to Δλ_{01} ≈ 0.27 μm, Δλ_{11,th} = 0.04 μm < Δλ_{11} ≈ 0.10 μm, and Δλ_{02,th} = 0.003 μm < Δλ_{02} ≈ 0.06 μm. These theoretical wavelength shifts are strictly due to electromagnetic phenomena and do not take into account any spectral variations of the QD absorption or any fabrication/material variations. In Figs. 2(a) and 2(b), the absorption intensity ratio of the first (λ_{01,th}) to the second (λ_{11,th}) resonance is 2.6 for t = 0.1 μm and 0.72 for t = 1.3 μm, roughly close to 1.8 for t_{0.1}- and very close to 0.71 for t_{1.3}-MPC device, respectively. Also, the variation of peak width with change of k is similar and consistent. From these results and the data in Table I, therefore, it can be concluded that the experiment in Fig. 2(a) and the simulation in Fig. 2(b) agree qualitatively.

For λ_{01} ≈ 8 μm, δ_{01} from Eq. (1) is ~7.2 μm, almost the same for both the QD stack and the top contact layer, so the electric fields of the SPW extend well into the semiconductor substrate beyond the 1.9 μm-thick QD stack and would be expected to provide strong SPW coupling, as confirmed with t_{0.1}-MPC. As seen in the inset of Fig. 3, however, the regime of t ≈ 1.3 μm that is still considerably less than δ_{01} is quite complex; a dramatic reduction of absorption and λ_{01} shift is evident. In the simulation, a larger Δ(√ε_{ij}) induces this reduction at even smaller t. The spatial overlap between the SPW and the QD stack in the presence of the contact layer is not the major issue responsible for the reduction of the photoresponse in Fig. 2(a). This is a leaky mode regime where the SPW excited at λ_{01} along the MPC/lower-index contact layer interface is strongly coupled to the unconfined radiation in the high-index GaAs substrate. For this range of t, therefore, the coupling to the QDs is reduced. The comparatively minor difference of photoresponse between t = 0.1 and 1.3 μm at λ_{11} in Fig. 2(a), where Δ(√ε_{ij}) is much smaller (~ -0.08) is additional evidence supporting the role of the antiguiding. For larger t (≳ δ_{01}), much of the SPW field is contained within the contact layer, and the responsivity is lower because of the poor spatial overlap to the QD stack as well as to free carrier absorption in the contact layer.

In summary, the effects of a 2.5 μm-period, 2D MPC integrated atop a Si-doped GaAs top contact layer of an InAs QDIP on a semi-insulating substrate have been investigated. The increase of the top contact layer thickness from 0.1 to 1.3 μm causes a blue shift of the resonance wavelengths of SPWs excited at the MPC/QDIP interface and a significant reduction (~50%) in the detectivity of the QDIP. This is explained with the leaky mode characteristics in the antiguide structure that consists of MPC/low-index contact layer/high-index substrate, arising from free carrier contributions to the dielectric function of the contact layer, as confirmed in simulation. The spatial variation of the dielectric function of a layer structure near a plasmonic coupler is important for the optimal SPW coupling between them.

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14. The plasma and the scattering frequency used in the simulation were 1.4 × 10^{16} and 8.3 × 10^{12} Hz, respectively.