Mid-infrared transmission enhancement through sub-wavelength metal hole array using impedance-matching dielectric layer

S.C. Lee, E. Plis, S. Krishna and S.R.J. Brueck

The mid-infrared transmission through a 3.7 μm period, two-dimensional sub-wavelength Au metallic hole array integrated on a GaSb/InAs strained layer superlattice nBn photodetector is measured. The surface plasmon-polariton excitation on the Au film induces a peak transmission in the 200 K detector response at 4.2 μm. This transmission is enhanced threefold by the insertion of a SiN_x layer between the Au film and the substrate for impedance matching analogous to antireflection coating.

Introduction: Recently, surface plasmon-polariton (SPP) coupling of light to collective excitations of the electrons at a metal surface has been extensively studied for its potential application to micro- and nano-photonics [1]. When a metal film is penetrated with a two-dimensional (2D) array of holes forming a metal photonic crystal (MPC), SPP coupling induces extraordinary transmission at particular wavelengths correlated to the hole period. A significant current issue for this phenomenon is the enhancement of transmission sufficient for device applications, such as photodetectors. An MPC thicker than skin depth has two different decoupled SPP excitations on a semiconductor; one associated with the front air/metal interface and the other with the metal/semiconductor interface at the back which is important with its near-field effects into the substrate [2]. In this Letter, we focus on the SPP on the air/metal interface. If an MPC is integrated on a semiconductor photodetector, the light from this SPP coupling mode must pass through the air/semiconductor interface at the bottom of the hole to reach the underlying photodetector. However, this interface is generally characterised by a large discontinuity in refractive index which inherently causes low transmission even though the SPP coupling itself can be very strong. In this Letter, the impedance mismatch owing to the large index discontinuity is relieved with the insertion of a dielectric film between the MPC and the semiconductor. In simulation, the optimal matching condition is achieved by controlling its thickness to a quarter wavelength at the peak transmission, which is analogous to antireflection coating. This is examined with a 3.7 μm period square MPC integrated on a GaSb/InAs strained layer superlattice (SLS) nBn photodetector [3]. The observed enhancement using this dielectric matching layer is as much as a factor of three, up to ∼55% transmission.

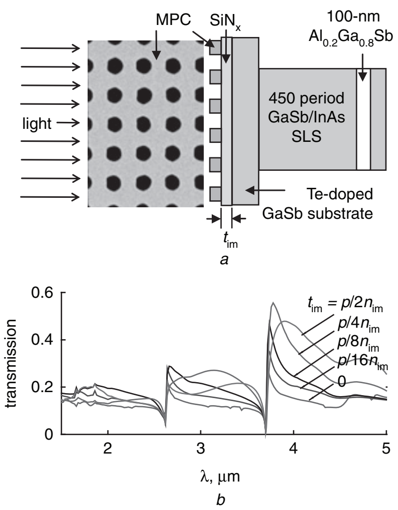

Fig. 1 *Cross-sectional schematic of MPC/SiN_x structure integrated on backside of nBn detector (right), and top-view SEM image of 3.6 μm period, 200 nm-thick Au MPC (middle) (Fig. 1a); and plot of wavelength against transmission of MPC on GaSb substrate having same structure as that in* a*, calculated by RCWA with variation of* t_{im} *in* a *(Fig. 1b)*

Arrows indicate dips due to Wood's anomaly. A peak at ∼2.7 μm is from SPP coupling along second nearest holes in diagonal direction

Design and fabrication: Fig. 1*a* shows the schematic sample structure, with a top-view scanning electron microscope (SEM) image of a 3.7 μm period (p), square MPC fabricated into a 200 nm-thick Au film on the backside of the photodetector. This period was set to the wavelength at the peak response of the nBn detector. The hole diameter of the MPC is ∼1.8 μm. A SiN_x film highly transparent in mid-infrared was employed for impedance matching.

Fig. 1*b* is the simulated spectral transmission through the MPC having the same structure as that in Fig. 1*a* on a bare GaSb substrate, calculated for different thicknesses of the SiN_x film, t_{im}, by rigorous coupled-wave analysis (RCWA). The refractive indices of SiN_x and GaSb (n_{im} and n_{sub}) were taken as 1.8 and 3.7 [4]. In Fig. 1*b*, the transmission enhanced by the SPP coupling on the front air/metal surface increases with t_{im} having the highest peak around 3.74 μm and is maximum at $t_{im} = p/4n_{im} = 513$ nm, where the enhanced transmission is 1.9× that for $t_{im} = 0$. Relying on this result, $t_{im} = p/4n_{im}$ was set for the optimal impedance matching in the experiment below.

To examine the impedance matching shown in Fig. 1*b*, a GaSb/InAs SLS nBn detector, operating at high temperatures with low noise, was employed [3]. The nBn detector was grown on a double-side polished GaSb(001) substrate by molecular beam epitaxy. The active region consists of 450 periods of an undoped GaSb (eight monolayers)/InAs (eight monolayers) SLS with a 100 nm-thick $Al_{0.2}Ga_{0.8}Sb$ barrier layer. The area is 410 × 410 μm^2. Fig. 1*a* includes a schematic illustration of the measurement setup. The 200 K spectral response of a bare nBn detector (S0), the detector with an metal MPC only (S1), and the detector with both a metal MPC and an ∼510 nm-thick SiN_x film for impedance matching (S2), were measured using a Nicolet 670 Fourier transform infrared spectrometer.

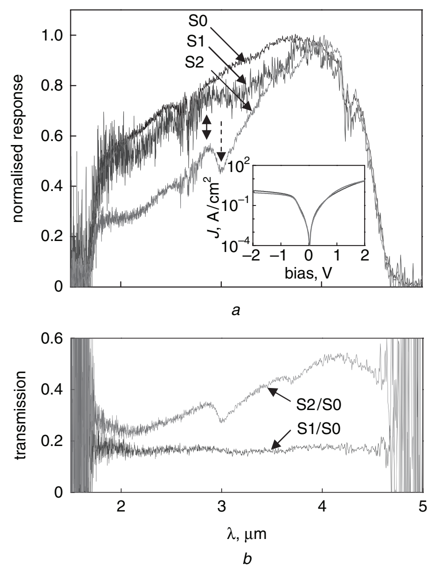

Fig. 2 *Spectral response of S0 through S2 at 200 K for bias of −0.6 V; and transmission of S1 and S2, obtained from Fig. 2a with normalisation by that of S0 in the same Figure*

a Spectral response of S0 through S2 at 200 K for bias of −0.6 V
Solid double head arrow indicates peak at 2.8 μm from SPP coupling between holes along diagonal direction shown in Fig. 1*a*
Dashed arrow indicates dip at 3.0 μm which is due to SiN_x layer
Inset: *I-V* measurement of three samples at 200 K
b Transmission of S1 and S2, obtained from *a* with normalisation by that of S0 in same Figure

Measurements and discussion: Fig. 2*a* presents the spectral response of S0, S1 and S2 at 200 K at a bias of −0.6 V. Each spectrum was individually normalised to its highest intensity. The spectral response of S0 is similar in line shape, temperature and bias dependence to the structures reported previously [3]. The response ranges from the bandgap of GaSb (∼1.7 μm) to the SLS cutoff wavelength, λ_c, ∼ 4.7 μm. The inset shows an *I-V* measurement at the same temperature. Because of the $Al_{0.2}Ga_{0.8}Sb$ barrier layer near the top surface in Fig. 1*a*, the *I-V* curves are asymmetric and have lower dark current density at negative bias for all three samples. In Fig. 2*a*, the line shapes and peak positions of all three samples are not identical. Especially, S2 has very different line shape from the other two. Thus, the presence of the SiN_x film significantly affects the overall line shape. In Fig. 2*a*, S1 and S2 have peak wavelengths near 3.9 and 4.0 μm, respectively, whereas the peak response of S0 is around 3.7 μm. This means that the MPC induces peak shift in spectral response.

Fig. 2*b* shows the spectral response of S1 and S2 normalised with respect to S0. This corresponds to the relative spectral transmission curves of the MPC in S1 (S1/S0) and the MPC/SiN_x in S2 (S2/S0) eliminating any GaSb substrate effects. The transmission curve of S2/S0 in Fig. 2*b* has a peak transmission wavelength, λ_T, at ~4.2 μm, slightly shifted from the peak response wavelength observed in Fig. 2*a* by ~0.2 μm. The rough coincidence of the peak wavelength with the abrupt drop of the detector response around λ_c, induces an apparent additional red shift. Then, the resulting variation of peak wavelength by the MPC and the SiN_x film at 200 K is ~0.5 μm from 3.7 μm of S0 in Fig. 2*a* to $\lambda_T = 4.2$ μm of S2 in Fig. 2*b*.

Fig. 2*a* clearly reveals the role of MPC in peak wavelength shift correlated with *p*. First of all, $\lambda_T \sim p$ implies that the peak shift is caused by the SPP coupling on the front side of the MPC. The difference between λ_T and *p* is impacted by Fano interference effects that must be considered in the design of the target wavelength of the MPC for nBn detectors [5]. The dip at 3 μm in S2 of Fig. 2*a* is due to an absorption band in the SiN_x film. Besides, like the peak at 2.7 μm in Fig. 1*b*, the peak at 2.8 μm for S3 is a result of the SPP coupling corresponding to the diagonal periodicity of the holes shown in Fig. 1*a*.

Along with the peak wavelength shift, S2 has very different line shape and a larger peak intensity enhancement compared with S0 in Fig. 2*a*. While S1 shows a minor change in line shape around peak wavelength in Fig. 2*a*, S1/S0 does not reveal any noticeable peak in Fig. 2*b* in spite of its similar background level to that for $t_{im} = 0$ in Fig. 1*b*. In contrast, S2 exhibits the role of the MPC and the impedance matching layer very clearly; the transmission is selectively filtered by the MPC around the wavelength ~*p* and is significantly enhanced by the impedance matching layer, which considerably impacts the working wavelength range of the nBn detector suppressing the short wavelength response. As shown in Fig. 2*b*, the transmission at λ_T is increased from ~18 to ~55%. This corresponds to approximately three times enhancement at λ_T simply with the addition of the SiN_x film with a thickness $\sim p/4n_{im}$. Thus, the embedded SiN_x film effectively resolves the critical issue of the integration of an MPC on a photodetector due to the large index discontinuity at air/semiconductor interface, as an impedance matching layer. These qualitatively agree with the RCWA results of Fig. 1*b*. Such enhancement of transmission by impedance matching is a very important result, providing a strong potential of MPC for SPP coupling to photodetectors.

It has been reported that the insertion of a dielectric layer degrades the transmission of SPP coupling [6]. As seen in Figs. 1*b* and 2, however, it can positively contribute to the transmission if the matching condition is properly controlled. While the maximum transmission of ~ 55% in Fig. 2*b* is comparable to the transmission predicted for $t_{im} = p/4n_{im}$ by RCWA in Fig. 1*b*, the enhancement is significantly higher than can be explained simply with an analogy to antireflection coating. Further studies to understand this enhancement are presently under way.

Conclusion: The transmission through a 3.7 μm period, 2D array of circular holes fabricated through a 200 nm-thick Au film, which is integrated on the backside of a GaSb/InAs SLS nBn photodetector has been measured. A 510 nm-thick SiN_x layer corresponding to a quarter wavelength at the peak transmission has been inserted between the Au and the GaSb substrate for optimal impedance matching at the air/substrate interface on the backside of the Au film. At 200 K, this results in the reduced working wavelength range shifting to the peak at 4.2 μm and enhanced detector response up to three times corresponding to 55% transmission.

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