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Room temperature plasmon-enhanced InAs$_{0.91}$Sb$_{0.09}$-based heterojunction n-i-p mid-wave infrared photodetector

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(Received 2 December 2017; accepted 19 June 2018; published online 5 July 2018)

Middle wavelength infrared (MWIR) photodetectors have a wide range of applications, but almost all of them operate at low temperature due to the limit of materials and device structures. The capability of plasmonic structures to localize electromagnetic wave on the deep subwavelength scale provides the possibility for MWIR photodetectors operating at room temperature. Here, we report a high sensitivity room temperature MWIR photodetector which is an InAs$_{0.91}$Sb$_{0.09}$-based heterojunction n-i-p photodiode integrated with a Au-based two-dimensional subwavelength hole array (2DSHA). A room temperature detectivity of $0.8 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$ and a response time of 600 ns are achieved. The non-cooling high performance of 2DSHA-InAs$_{0.91}$Sb$_{0.09}$ based heterojunction photodetectors will make their applications easier, broader, and economic. Published by AIP Publishing. https://doi.org/10.1063/1.5018012

Middle wavelength infrared (MWIR, 3–5 $\mu$m) photodetectors have various applications in security, communication, medical diagnostics, and remote sensing. Most of the MWIR photodetectors operate at low temperature due to limited detection performance. Mercury cadmium telluride (HgCdTe/MCT) photodetectors have taken a dominant position in this detection performance. However, Al$_{0.15}$In$_{0.85}$As$_{0.9}$Sb$_{0.1}$ layers. A p-type (Be: $1 \times 10^{18}$ cm$^{-3}$) GaSb buffer layer (1 $\mu$m) is used as the bottom contact layer followed by a 40 nm p-doped (Be: $2 \times 10^{18}$ cm$^{-3}$) Al$_{0.42}$Ga$_{0.58}$Sb layer. To reduce dark current, some wide bandgap layers are introduced in this heterojunction. As shown in the schematic band diagram of this structure (left-bottom inset), the p-doped Al$_{0.42}$Ga$_{0.58}$Sb layer with a wide bandgap is used to reduce the dark current of electrons from the p side. The p-doped Al$_{0.15}$In$_{0.85}$As$_{0.9}$Sb$_{0.1}$ layer is inserted to limit type II electron-hole transitions between the Al$_{0.42}$Ga$_{0.58}$Sb and InAs$_{0.91}$Sb$_{0.09}$ layers.

The purpose of having only a 20 nm thick top n-type layer is to ensure more SPPs to interact with the active intrinsic absorptional InAs$_{0.91}$Sb$_{0.09}$ layer. The top and bottom ohmic contacts are 15 nm thick titanium (Ti) followed by 200 nm thick gold (Au). The 300–$\mu$m sized square mesas are defined by wet etching, followed by deposition of the
can be expressed as \( k_{app} = k_0 \sqrt{\varepsilon_m \varepsilon_d / (\varepsilon_m + \varepsilon_d)} \). At normal incidence (\( \theta = 0 \)), for the Au 2DSHA integrated on top of the sample with a hole period \( p \), the surface plasmon resonance (SPR) wavelengths are given by

\[
\lambda_{ij} = \frac{p}{\sqrt{1 + j^2}} \text{Re} \left( \frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} \right)^{1/2},
\]

where \((i, j)\) are the set of integers denoting the mode orders in \(x\) and \(y\)-directions, and \(\varepsilon_m(\varepsilon_d)\) is the permittivity of the metal (semiconductor). The permittivity of our sample in the wavelength range of interest is \( \sim 15.1 \) (the imaginary part is much smaller than the real part) while the permittivity of gold can be expressed by the Drude model

\[
\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\omega_c)},
\]

where \(\varepsilon_\infty = 1\) is the high frequency dielectric constant, \(\omega_p = 1.37 \times 10^{16} \text{ rad/s}\) is the plasma frequency, and \(\omega_c = 4.07 \times 10^{13} \text{ rad/s}\) is the collision frequency. Combining Eqs. (2) and (3), for the 2DSHA metallic structures with \( p = 900 \text{ nm} \), the SPR wavelength can be deduced as \(3.5 \mu m\) for the fundamental plasmon mode (\(\lambda_{10}\) or \(\lambda_{01}\)) at normal incidence, which is located around the peak photocurrent response of the InAs\(_{0.91}\)Sb\(_{0.09}\) based heterojunction \(n-i-p\) photodiode. At plasmonic resonance, the confinement of SPP waves inside dielectric medium can be described by the SPP penetration depth (\(\delta_d\))

\[
\delta_d = 1 \left| \frac{\varepsilon'_m + \varepsilon_d}{\varepsilon'_d} \right|^{1/2},
\]

where \(\varepsilon'_m \) is the real permittivity of the gold, \(\varepsilon_d \) is the permittivity of the \(n-i-p\) sample, and \(k_0\) is the wavevector in the free space. The penetration depth of the surface plasmons in the InAs\(_{0.91}\)Sb\(_{0.09}\) based heterojunction \(n-i-p\) sample at \(3.5 \mu m\) is found to be \(\sim 1 \mu m\). This serves as the guide for choosing the thickness of the intrinsic absorption layer in our \(n-i-p\) devices. In experiments, we also fabricated other 2DSHA hetero \(n-i-p\) devices with hole periods of \( p = 550, 1280, \) and \(1500 \text{ nm}\) for comparison. For all the 2DSHAs, the width of the square hole is close to half of \( p \) to give better performance.

Figure 2 shows the photocurrent spectra (measured by FTIR with an MWIR focus lens) of the InAs\(_{0.91}\)Sb\(_{0.09}\) based heterojunction \(n-i-p\) (black curves) and the 2DSHA-hetero \(n-i-p\) (red curves) devices under zero bias, measured at room temperature (293 K) and \(T = 77 \text{ K}\), respectively. For room temperature operation, the InAs\(_{0.91}\)Sb\(_{0.09}\) based heterojunction \(n-i-p\) photodiode, which will then be referred to as “the reference,” is observed to exhibit broadband response from about \( 2 \mu m \) to \(5 \mu m\) with a photocurrent peaked at a wavelength of about \(3.5 \mu m\). When temperature is decreased to \(77 \text{ K}\), the cutoff wavelength is shifted from \(5 \mu m\) to about \(4 \mu m\) due to bandgap broadening of the InAs\(_{0.91}\)Sb\(_{0.09}\) layer. At \(77 \text{ K}\), the photocurrents are much larger than those at room temperature due to the increased carrier mobility (increased carrier velocity). The absorptions at about \(2.7 \mu m\), \(3.3 \mu m\), and \(4.3 \mu m\) by the environmental air are also observable in the photocurrent spectra of both temperatures.
The electric field enhancement factors, defined as $B$ with $p$ as a parameter, were obtained using full-wave simulations (FDTD) for the 2DSHA structures in Fig. 3. To gain insights into the enhanced electrical field, we present numerical calculations of the electric field in the interface between the metal and the dielectric. To gain a further understanding, we simulated reflectance spectra of the 2DSHAs with $p = 900$ nm at zero bias for the devices corresponding to (a)–(d), respectively.

It is noted that all the four 2DSHA-hetero $n$-$i$-$p$ photodetectors show obvious photocurrent enhancement although the one with the period of 900 nm shows the highest. Specifically, the average enhancement factors are in the range of 3–4 for the 2DSHA-hetero $n$-$i$-$p$ photodetector with $p = 900$ nm and 1–2 for the other three photodetectors with $p \neq 900$ nm. As SPR occurs, the optical electrical field (light density) becomes very large especially at around the interface between the metal and the dielectric. To gain insights into the enhanced electrical field, we present numerical simulations (FDTD) for the 2DSHA structures in Fig. 3. The electric field enhancement factors, defined as $B = |E_j|/|E_{0j}|$, at $\lambda_0 = 3.5 \mu m$ and the detuning $|\lambda_{SPP} (i,j) - \lambda_0|$ of the fundamental and high order SPP modes from $\lambda_0 = 3.5 \mu m$ as a function of hole period of the 2DSHAs are shown in Fig. 3(a). It is clearly seen that maximum field enhancement is obtained when the fundamental resonance matches $\lambda_0$ at $p = 900$ nm, and field enhancements in other hole periods also exist due to the contributions from different plasmonic modes. The detuning of the fundamental SPP mode from $\lambda_0 = 3.5 \mu m$ also has the smallest value when the period $p = 900$ nm. The numerically calculated electric field enhancements of the periodic metal hole array for the 2DSHA with $p = 900$ nm are also shown in Fig. 3(b), where the electric field values are taken from the hot-spot point (for an unit cell, $x = p/2$, $y = 0$, and $z = 0$) with the position indicated in the inset. It is obvious that in addition to the fundamental mode, other higher order plasmonic modes of the 2DSHA also contribute to the field enhancement.

Ideally, if the enhancement occurs due to strong light confinement near the metal-dielectric interface at resonance only, it then follows that the enhancement should be within a narrow wavelength range around those resonance modes. However, this is not the case as enhancements are observed over a broad wavelength range. This broadband character mainly comes from the continually distributed incident angles in the FTIR measurements (mainly from the focus lens). To gain a further insight into this, the SPRs of the 2DSHAs have been separately demonstrated by measuring the reflectance spectra on both this hetero $n$-$i$-$p$ sample and Si substrates [Fig. 4(a)]. The SPR modes (marked fundamental modes as examples) on Si show obvious blue-shift compared to those on hetero $n$-$i$-$p$ samples as the permittivity of Si (11.8) is smaller than that (15.1) of the hetero InAsSb $n$-$i$-$p$ sample [abide by Eq. (2)].

![FIG. 2. Room temperature photocurrent spectra of 2DSHA-hetero n-i-p photodetectors with periods of (a) 900 nm, (b) 550 nm, (c) 1280 nm, and (d) 1550 nm at zero bias. (e)–(h) Photocurrent spectra at 77 K and zero bias for the devices corresponding to (a)–(d), respectively.](image)

![FIG. 3. Field enhancement in the 2DSHAs. (a) Field enhancement factors at $\lambda_0 = 3.5 \mu m$ and the detuning of fundamental and higher order SPP modes from $\lambda_0 = 3.5 \mu m$ as a function of hole period. The theoretical results (solid lines) are in agreement with those obtained from FDTD simulations (triangle markers). (b) Electric field enhancement spectrum of the 2DSHA with $p = 900$ nm at the indicated position for a unit cell $x = p/2$, $y = 0$, and $z = 0$ (metal-semiconductor interface).](image)
resulting in broadband enhancement in photocurrent as shown in Fig. 2. Other factors, such as localized surface plasmons (LSPs), Fabry-Perot (FP) resonance, and prolonged light path can also contribute to the photocurrent enhancements, but their contributions are not significant in our case.

Finally, we used a 700°C blackbody radiation source to characterize the responsivity and detectivity of the 2DSHA-hetero n-i-p photodetector with $p = 900$ nm and the reference at room temperature under biased voltages from $-350$ mV to 350 mV. The room temperature responsivities $R = I_s/P$, where $I_s$ is the signal current and $P$ is incident radiation power on the detector calibrated by a standard power meter (OPHIR PHOTONICs) of the two devices are presented in Fig. 5(a). As shown, the photoresponses of both devices increase with the increasing reverse voltage owing to the increased electric field (increased carrier velocity), demonstrating that the photocurrent mainly comes from the drifting of photon-excited carriers. It is found that the responsivity of the 2DSHA-hetero n-i-p photodetector increases when the biased voltage varies from positive to negative and tends to saturate at about $-150$ mV at a value of 0.85 A/W, as compared to 0.15 A/W for the reference at the same bias. It is noted here that the responsivity of the reference device is saturated at around $-350$ mV with a value of only 0.3 A/W, while that of the plasmonic device is saturated at about $-150$ mV with a much larger value. As the current-voltage curves [inset of Fig. 5(a)] confirm that the plasmonic and reference devices have similar dark current characteristics, the difference in the saturation voltages of the responsivities is primarily due to the plasmonic effect. In the 2DSHA n-i-p device, most EHPs are mainly generated in the absorbing layer near the metal-semiconductor interface and the electrons can be fast collected by the electrode. This will lead to a lower bias voltage for the electrons to reach the saturated drift velocity as $v = \mu E$. The room temperature blackbody detectivity $D = R_s/\sqrt{2qJ + 4kT/R}$, where $q$ is the electronic charge, $J$ is the dark current density, $R_s$ is the dynamic resistance, $A$ is the area, and $R_i$ is the photo-current responsivity of the 2DSHA-hetero n-i-p photodetector is $0.80 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$ at $-150$ mV [Fig. 5(b)], compared to $0.12 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$ of the reference under the same bias voltage, corresponding to 6.6x enhancement. The external (EQE) quantum efficiencies $\eta_E = R_s/hc/(\lambda q)$, where $h$ is the Planck constant, $c$ is the speed of light in vacuum, $\lambda$ is the wavelength) at 3.5 $\mu$m are presented in Fig. 5(c) with the maximum value of 30% occurring at $-150$ mV, corresponding to about 5x enhancement. It is noted that the EQE for the reference device is only $\sim 2\%$ at zero bias, which may due to the barriers in the hetero n-i-p structure. We also measured the line widths of the impulse responses of the 2DSHA-hetero n-i-p device and the reference at zero bias with a 4.77 $\mu$m quantum cascade laser (QCL) pulse (200 ns in width). They are 600 ns for both devices [Fig. 5(d)], demonstrating a fast response to the input signal. These measured results show that the performance of the 2DSHA-hetero n-i-p photodetector can be improved a lot without sacrifice of the speed.

In summary, metallic subwavelength hole array enhanced InAs$_{0.91}$Sb$_{0.09}$ based heterojunction n-i-p photodetectors have been realized, and a room temperature detectivity of $0.8 \times 10^{10}$ cm Hz$^{1/2}$ W$^{-1}$ has been achieved with a response speed of 600 ns. This work opens a way of developing high sensitivity room temperature MWIR photodetectors with high detectivity meanwhile not reduced response speed. The realization of a room temperature mid-wave infrared photodetector makes the application systems more economic and easily extended to more application domains.

The authors thank Dr. Jean-Luc Reverchon and Dr. Philippe Bois of III–V lab France for their kind support and...
help and Professor Wang Qijie, Dr. Guozheng Liang, and Dr. Meng Bo for their assistance. This work was supported by the Economic Development Board (NRF2013SAS-SRP001-019), the Ministry of Education (RG86/13), and AOARD (FA2386-17-1-0039).

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