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Detectivity of plasmonic enhanced photodetectors based on non-degenerate two-photon absorption process

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ABSTRACT

Mid-infrared photodetectors are the subject of many research efforts within the last two decades for enhancing their operating parameters such as temperature stability, detectivity and quantum efficiency. This is due to their wide range of applications like biosensing, night vision, and short range communication. However, mid-infrared photons have much smaller energy compared with the band gap energy of well known semiconductors including III-V and II-VI families. One way to overcome this problem is to utilizing quantum confinement effects by absorbing a photon through the intersubband transition of a conduction electron or valance hole. Fabricating devices at the nanoscale size to achieve quantum confinement is costly and imposes limitations for further device preparation. In addition, the optical properties of quantum confined devices are sensitive to nanoscale geometrical parameters which make them vulnerable to fabrication imperfections. The other approach of detecting mid-infrared light is by exploiting the non-degenerate two-photon absorption process (TPA). Two photons with different energies can be absorbed simultaneously by a semiconductor with the band gap energy less than the overall energy of two photons. Thus, a mid-infrared photon as the signal can be detected by a bulk semiconductor with much larger band gap energy when a near-infrared photon as the gate assists the absorption process through TPA.

1. INTRODUCTION

IR photodetectors are heavily investigated to enhance their operating parameters such as temperature stability [1, 2], detectivity [3, 4] and quantum efficiency [5]. This is due to their wide range of applications like biosensing [6], night vision [1, 7, 8], and short range communication [2, 9]. Two photons with different energies can be absorbed simultaneously by a semiconductor with the band gap energy less than the overall energy of two photons [10]. Thus, a mid-infrared photon as the signal can be detected by a bulk semiconductor with much larger band gap energy when a near-infrared photon as the gate assists the absorption process through TPA. The optical response of the TPA detector can be dynamically tuned by adjusting the gate wavelength. The tunability feature of a TPA detector is valuable in biosensing since many biological substances have fingerprints in mid-infrared region. A TPA detector can also be considered as an all optical switch with a mid-infrared signal and a gate at the optical communication frequency [11]. Since the TPA coefficient is proportional to the gate optical intensity, an optical coupler is needed to provide a strong overlap between signal and gate optical fields by redefining the signal and gate field profiles at the absorbing region.

2. TPA PROCESS

A surface plasmon coupler can be a perfect candidate for achieving high internal quantum efficiency [12, 13] compared with a photonic coupler by focusing the signal and gate optical fields into a subwavelength region while boosting the absorption process as a result of field enhancement. As a result of using surface plasmons, the detector can be thinner [14] as suggested schematically in figure 1:

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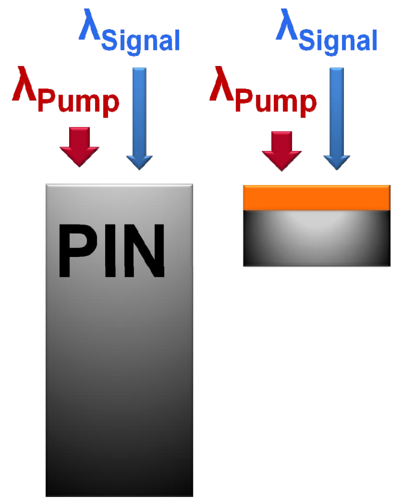

Figure 1 The schematic of the surface plasmon effect on TPA detector.

In this paper, we investigate the effect of surface plasmon enhancement on the specific detectivity of a photodetector based on TPA process. The schematic of TPA process is shown in shown in figure 2 which shows the energy diagram of material band gap, pump and signal energies.

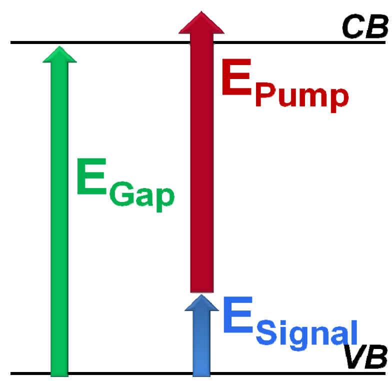

Figure 2 The energy diagram showing the pump and signal energies. The detector is optically biased by pump and can detect the signal at infrared region of light spectrum.

The different absorption processes in the semiconductor can be described by the following set of equations:

$$\frac{dI_s}{dz} = -\alpha_U(\omega_s)I_s - \alpha_{TPA}(\omega_s,\omega_s)I_s^2 - 2\alpha_{TPA}(\omega_s,\omega_g)I_g I_s \qquad (1)$$

where, I_s (I_g) is the optical signal (gate) intensity with photon energy $\hbar\omega_s$ ($\hbar\omega_g$), $\alpha_U(\omega) = \alpha_0 \exp\left((\hbar\omega - E_g)/E_U \right)$ is Urbach absorption coefficient in a semiconductor with absorption at the band gap edge α_0 and Urbach energy E_U. $\alpha_{TPA}(\omega_1,\omega_2) = K\frac{\sqrt{E_p}}{n_1 n_2 E_g^3}F(x_1,x_2)$ is non-degenerate TPA coefficient under the assumption of parabolic conduction and valance bands in a direct band gap semiconductor. $K = 1940\ cmGW^{-1}eV^{5/2}$ is a material independent constant. x_1, x_2 are the ratio of photon energies to the band gap energy with the condition $x_1 + x_2 > 1$ and $F(x_1,x_2) = \frac{(x_1+x_2-1)^{3/2}}{2^7 x_1 x_2^2}\left(\frac{1}{x_1}+\frac{1}{x_2}\right)^2$. n_1, n_2 are the background refractive indices of the semiconductor at the corresponding photon energy. In most of the photodetectors, photons are converted to photocurrent with high internal quantum efficiency ($\eta_0 \cong 1$).

3. DARK CURRENT COMPONENTS

In a pn junction, there are several current components which contribute in dark current [15]. Diffusion current noise is $< i_n^2 >_D = \frac{4k_B T}{R_0}$ where $R_0 = \frac{k_B T}{qJ_s}$ zero bias differential resistance is and $J_s = q\left(\frac{D_h P_n}{L_h} + \frac{D_e n_P}{L_e}\right)$ is the saturation current. The blackbody radiation current noise has the expression $< i_n^2 >_{BB} = 2qJ_{BB}$ where $J_{BB} = e\int_0^{\lambda_c} \frac{8\pi c n_0^2 (1-\exp(-\alpha_{TPA} L^*))}{\lambda^4 \left[\exp\left(\frac{hc}{\lambda k_B T}\right) - 1\right]} d\lambda$ is the blackbody photocurrent and $\lambda_c = \frac{hc}{Eg - \hbar\omega_g}$ is the cut off wavelength in which the responsivity of the detector goes to zero. The Urbach absorption tail contributes in current noise as $< i_n^2 >_U = 2q\, J_U$ where $J_U = qG(L_e + L_h)$ is Urbach current density and $G = \frac{I_g(1-\exp(-\alpha_U d^*))}{\hbar\omega_g d^*}$ is carrier generation rate. The tunneling current noise is calculated by the expression $< i_n^2 >_T = \frac{4k_B T}{R_0}$ where R_0 is the differential resistance of the tunneling at zero bias. The current Responsivity $R_I = \frac{q\lambda}{hc}\eta(d^*)$ is related to the detectivity of the photodetector through $D^* = \frac{R_I\sqrt{A\Delta f}}{< i_n^2 >}$ where $< i_n^2 >$ is the sum of the noise components contributed in dark current.

4. RESULTS AND DISCUSSION

The different dark current components for InGaAs based TPA detector are shown in figure 3. The tunneling current is very small compared with other mechanism. By increasing the pump power, degenerate TPA of pump becomes dominates whereas for smaller pump power, Urbach mechanism is important.

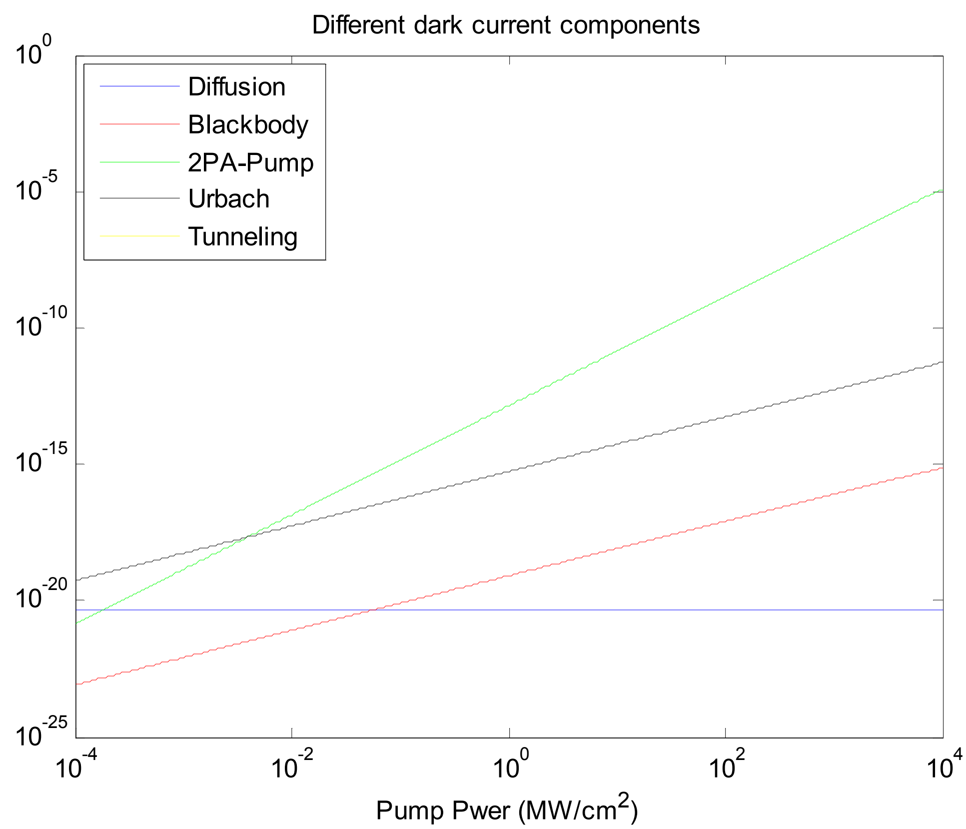

Figure 3 Different components are dark currents in InGaAs based infrared detector.

The surface plasmon coupler (figure 4) consists of two Bowtie antennas with cross polarization as in [11]. One of the antennas is assigned to collect pumping light into gap region where the TPA semiconductor is placed. The other is responsible to couple infrared light (long wavelength) into near field region and focus it at the gap of the antenna.

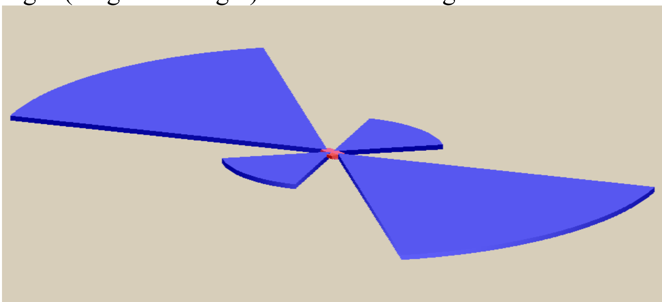

Figure 4 The schematic of the surface plasmon coupler consists of two Bowtie antennas with cross polarization. Strong field enhancement can be achieved at the gap between antennas.

Here the results of TPA quantum efficiency in the presence and absence of surface plasmon coupler shown in figure 5. The quantum efficiency has at least 10 times enhancement compared with using no plasmonic coupler.

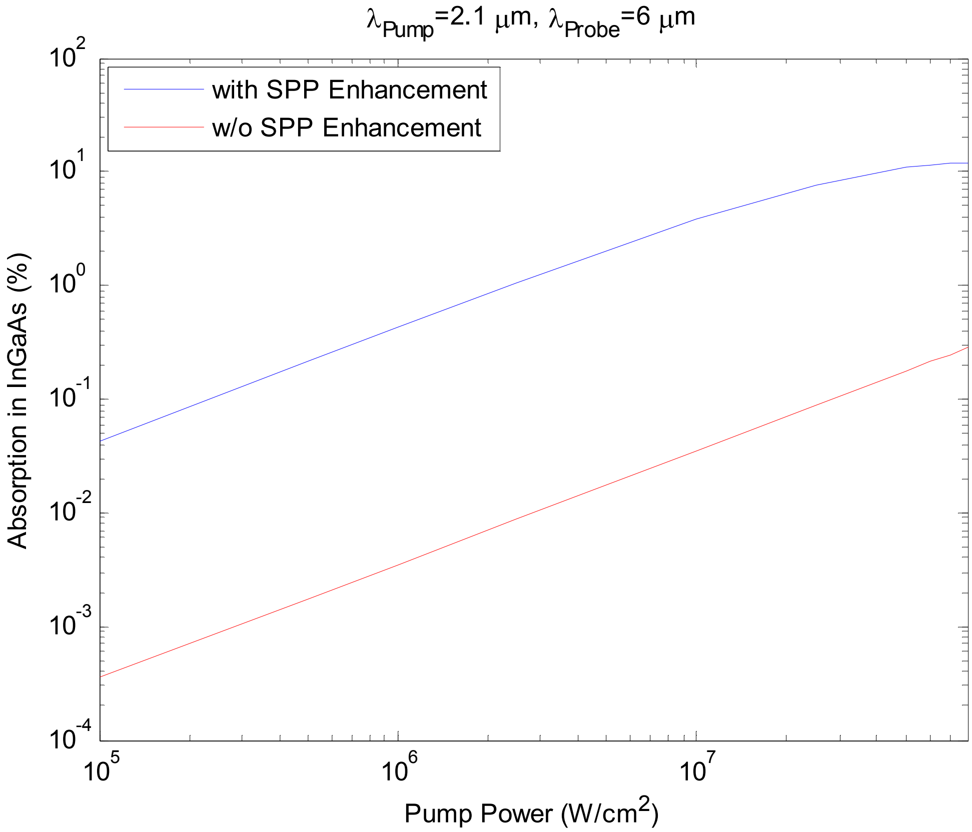

Figure 5 TPA quantum efficiency in the presence and absence of surface plasmon coupler.

The specific detectivity is shown in figure 6. Due to using plasmonic coupler, the overall detector performance improved significantly.

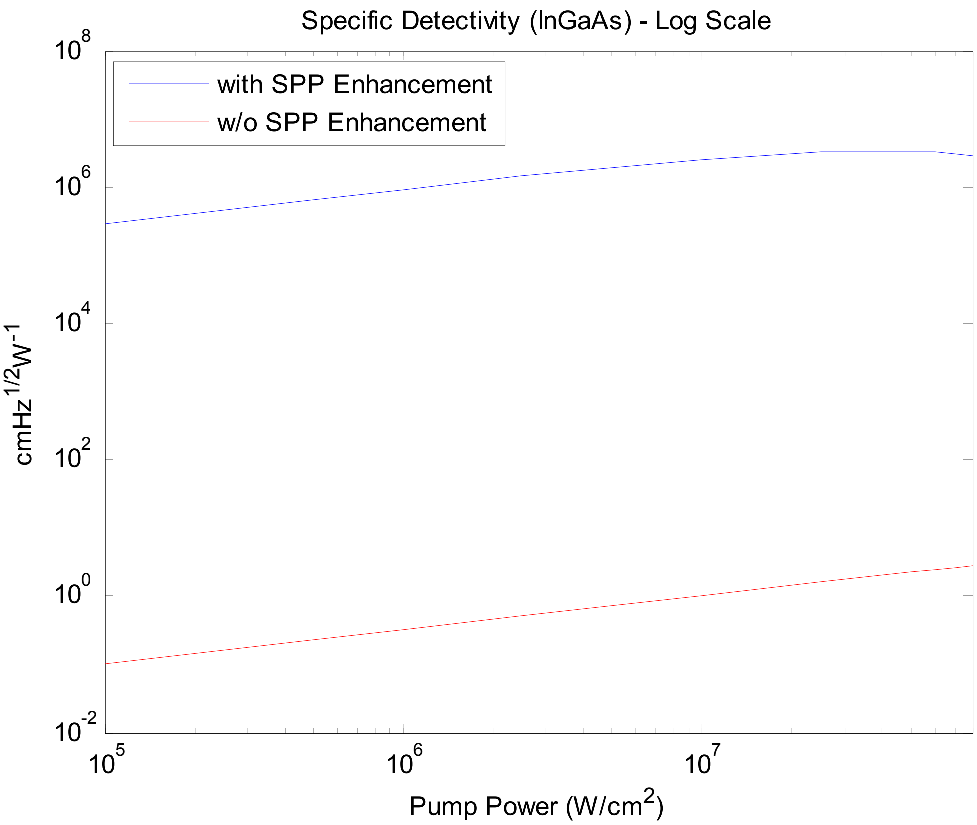

Figure 6 Calculated specific detectivity in the presence and absence of surface plasmon coupler.

5. CONCLUSION

Two photon absorption is a nonlinear process in which light at infrared frequency can be absorbed by a large band gap semiconductor. The quantum efficiency of TPA process is very low which result in using very high power gate power. As a result, the detector cannot be efficient. FDTD simulation shows that by using surface plasmon coupler, pump intensity could be enhanced and higher overlap integral between signal mode and pump mode can be achieved. As a result the absorption and detectivity of the detector can be dramatically enhanced.

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