Plasmonic photodetectors based on asymmetric nanogap electrodes

Junyu Ge, Manlin Luo, Wanghui Zou, Wei Peng*, and Huigao Duan

Key Laboratory for Micro-/Nano-optoelectronic Devices of Ministry of Education, School of Physics and Electronics, Hunan University, Changsha 410082, China

*E-mail: pengwei@hnu.edu.cn

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In recent years, the rapid development of optical communications, signal processing, and sensor systems has proposed higher requirements for the performance of semiconductor photodetectors. Photons with energies below the Si bandgap ($E_g = 1.12$ eV) cannot be harvested by a Si photodetector, which limits its application to optical communications and infrared detection. This limitation of the Si photodetectors can be relaxed by harvesting the energy of photoelectrons ejected from a metal. Hot electrons excited by plasmon resonance in metallic nanoelectrodes can be converted into a photocurrent, even when the photon energy is lower than the bandgap of the semiconductor. There are two characteristics making the plasmonic photodetector an efficient device: the intense light-focusing properties of a plasmonic nanoantenna allow more photons to be coupled and absorbed by the device, which means more photons can be converted into a photocurrent, and efficient collection of the conductive carriers can be achieved by a certain device structure that makes use of the hot carriers produced in the relaxation of plasmons.

Recent studies have already revealed the potential importance of plasmon resonances in near-infrared optical absorption enhancement. Halas et al. accomplished an active optical antenna device with Au resonant antennas fabricated on an n-type Si substrate, and achieved a tunable peak response at a wavelength range of 1250–1600 nm. Nevertheless, the device structure can restrict the responsivity of the device. In this paper, a type of plasmonic photodetector based on asymmetric nanogap electrodes is proposed. Owing to this structure, the device achieves responsivities as high as 0.45 and 0.25 mA/W for wavelengths of 1310 and 1550 nm, respectively. These insights can aid the realization of efficient plasmon-enhanced photodetectors for infrared detection.

Fig. 1. Plasmonic photodetector based on asymmetric nanogap electrodes. (a) Device structure. The dimension of the structure is illustrated on the top-right. Here, $W_p$ is the width of the plasmon electrodes, $W_c$ is the width of the collection electrodes, $G$ is the gap between the electrodes, and $H$ is the height of the electrodes. (b) Band diagram of the device. The photocurrent is generated in five consecutive steps.
The hot electron momenta in the semiconductor-metal interface again and are collected as a photocurrent. Finally, the carriers reach a semiconductor-metal interface again and are collected as a photocurrent.

As depicted in Fig. 2, the constant energy outline contains all of the possible terminations of the allowed electron momenta at a given kinetic energy. In Au electrodes, the hot carriers emitted by photons have energy as below:

$$E_{\text{Kin, Au}} = E_{F, \text{Au}} + E = \frac{\hbar^2}{2m_e^*} (k_{\text{Au,x}}^2 + k_{\text{Au,z}}^2).$$  (1)

Here, $\hbar$ is the reduced Planck’s constant, $m_e^*$ is the effective mass of the electron, and $k_{\text{Au,x}}$ and $k_{\text{Au,z}}$ are the hot electron momenta in the x- and the z-directions, respectively. The total momentum of a hot electron is equal to the quadratic sum of the momenta in the x- and the z-directions:

$$k_{\text{Au}}^2 = k_{\text{Au,x}}^2 + k_{\text{Au,z}}^2.$$  (2)

Once the electron is injected into the Si substrate, both its kinetic energy and momentum would change relatively. The kinetic energy is calculated as

$$E_{\text{Kin, Si}} = E - \Phi_B = \frac{\hbar^2}{2m_e^*} (k_{\text{Si,x}}^2 + k_{\text{Si,z}}^2).$$  (3)

Again, the total momentum of the hot electrons in Si is calculated as the following:

$$k_{\text{Si}}^2 = k_{\text{Si,x}}^2 + k_{\text{Si,z}}^2.$$  (4)

The hot electron momenta in the x-direction are fixed when electrons are injected into the semiconductor substrate from the metallic electrodes, which defines the escape cone for the electrons. Hot electrons can escape only when $k_{\text{Au,x}} < k_{\text{Au, max}}$, which limits the probability of emission to a solid angle $\Omega$. Thus, regardless of the reflecting events, the emission probability is:

$$P(E) = \int_0^{2\pi} \int_0^{\pi} \sin \theta d\theta d\phi \frac{1}{4\pi} = \frac{1}{2} (1 - \cos \Omega).$$  (5)

However, despite the fact is that the hot electrons arriving at the metal/semiconductor interface can be reflected in the vast majority of cases, there is still a possibility for them to pass the Au–Si interface after multiple times of scattering events, and two assumptions are made based on this phenomenon:

1) If the hot electrons cannot travel through the Au–Si interface, they can make it to the interface in an elastic collision; (2) The electrons cannot travel through the Au-vacuum interface or escape into vacuum, but they can make it to the interface in an elastic collision.

Then, taking the reflecting events into account, the emission probability of a hot carrier every time is presented in Fig. 3 and the probability of emission is evaluated as:

$$P_i(E) = \begin{cases} P_i(E_0) = \frac{1}{2} (1 - \cos \Omega), & N = 0 \\ P_0 + (1 - P_0)P_1 + \cdots + P_N \prod_{m=1}^{N-1} (1 - P_m) & N > 0 \end{cases}.$$  (6)

$N$ is the total number of round trips before the excess energy of the carrier is reduced to $E = \Phi_B$. It is given by

$$N = \frac{L}{2H} \ln \left( \frac{E_0}{\Phi_B} \right).$$  (7)

where $L$ is the mean free path of the electrons, $H$ is the height of the electrodes, $E_0$ is the initial energy of the hot electrons, and $\Phi_B$ is the Schottky barrier.

The mechanism of the hot electrons traversing Si–Au interfaces is essentially the same with that of traversing Au–Si interfaces except for the travel direction. Moreover, the possibility of hot electrons injecting into the collection electrodes is defined as $P_0$.

The total internal quantum efficiency $\eta_{\text{total}}$ indicates the efficiency of hot carriers emitted into the semiconductor and collected by collection electrodes, which can be obtained by:

$$\eta_{\text{total}} = \frac{1}{P_0} \int_{\Phi_B}^{E_0} P_i P_{\text{th}} dE$$  (8)

The responsivity of the electrodes is given below:

$$R = \frac{q}{h} \times v \times A \cdot \eta_{\text{total}}.$$  (9)
where $h$ is Planck’s constant. With the above equations, the probability of hot carriers injected into the Si substrate can be obtained.

Figure 4 shows the field distributions of the device with the initial design that has the dimensions of $H = 30$ nm, $W_p = 150$ nm, $W_c = 1$ μm, and $G = 50$ nm. Figures 4(a) and 4(c) are the electric field and the magnetic field distributions of the plasmon electrodes, respectively. The electric field is inclined to distribute towards the edges of the electrodes, opposite to its magnetic field status, because $1/2\lambda_{SPP}$ fits along the width of the electrodes, which is evidence of the existence of surface plasmon resonance.21) Figures 4(b) and 4(d) are the two field distributions of the collection electrodes. Compared to the plasmon electrodes, the intensity of their electric field is significantly weakened. In the meantime, the 1 μm metallic electrodes no longer fit $1/2\lambda_{SPP}$.

Therefore, there are several maximums simultaneously in the magnetic field, and the plasmon resonance is reduced.

The light absorption is determined by the intensity of the electric field, as shown in this equation:20)

$$A = \frac{\iint \frac{\pi c}{\lambda} \text{Im}[E^2] \, dx \, dy \, dz}{\text{source power}}.$$

This enables us to analyze the performance of the devices.

As shown in Fig. 5, the relationships between the optical absorption and device dimensions are studied. In Fig. 5(a), the light absorption exhibits a $\cos^2 \theta$ angular dependence and the position of the peak value is relevant for the physical size of the device.

In Fig. 5(b), when the wavelength is 1310 nm, the absorption is improved with the growth of $H$, and remains the same since $H$ is more than 30 nm. On the contrary, the absorption is reduced with the growth of the electrode width, shown in Fig. 5(c), and the peak value appears with the electrode width $W_p = 90$ nm and electrode height $H = 25$ nm. When the wavelength is 1550 nm, the changing trend of the curve of the absorption is different. It has a negative relationship with $H$, and has a positive relationship with the electrode width. The peak value appears with the electrode width $W_p = 150$ nm and electrode height $H = 20$ nm. These provide valuable information for optimizing the device.

The relationship between electrode gap and absorption is shown in Fig. 5(d). When the nanogap is relatively small, its surface plasmon polaritons (SPP) will couple with the wavelength of 1310 nm, which enhances the electric field. For a gap is up to 200 nm, the coupling interaction of the nanogap and wavelength of 1550 nm is dominant,23) which proves that the optimized gap widths for the wavelengths of 1310 and 1550 nm are different. However, a wide gap will increase the energy loss during the transition, and the transition time will become longer when the electrode gap is broadened. Consequently, proper electrode gaps are needed.

The collection electrode width $W_c$ plays an important role in influencing the absorption as well. The net current is the difference between the photocurrent produced by the plasmon electrodes ($I_p$) and the one produced by the collection electrodes ($I_c$). Without a bias voltage, it reduces to zero when the absorption of the two electrodes is the same. Thus, the photocurrent $I_p$ is expected to be kept as small as possible, and this can be realized via reducing the absorption of the collection electrodes. The relationship between the width $W_c$ and the absorption of the collection electrodes is depicted in Fig. 6. The absorption cannot be neglected when $W_c$ is smaller than 1 μm and $I_p$ is offset by $I_c$, which leads to a decrease of...
Fig. 7. Internal quantum efficiency and emission probability of hot electrons as functions of the photon wavelength.

Table I. Three optimized devices with different device dimensions: height of electrodes \( H \) (nm), width of plasmon electrode \( W_p \) (nm), width of collection electrode \( W_c \) (µm), and electrode gap \( G \) (nm).

| Device      | \( H \) | \( W_p \) | \( W_c \) | \( G \) |
|-------------|--------|--------|--------|------|
| Device 1    | 30     | 150    | 1      | 50   |
| Device 2 (for 1310 nm) | 25     | 130    | 1      | 150  |
| Device 3 (for 1550 nm) | 20     | 160    | 1      | 200  |

In summary, a plasmonic Si photodetector with asymmetric nanogap electrodes is proposed and the physical mechanism of the photoelectric effect is studied. By decreasing the transmission length of the hot electrons to nanometer scales, the device achieves much higher responsivities with wavelengths of 1310 and 1550 nm. This ultracompact, CMOS-compatible Si based plasmonic photodetector can be readily integrated into on-chip optoelectronics, which will result in enhanced efficiencies and lower costs in optical communication systems.

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