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Hot-electron photodetection based on embedded asymmetric nano-gap electrodes

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ABSTRACT

Hot electrons generated from the nonradiative decay of surface plasmons can be employed in photodetection. However, only a small percentage of these hot electrons can be collected. In this paper, a type of hot-electron photodetector based on embedded asymmetric nano-gap electrodes is proposed which can enhance hot-electron collection efficiency. Due to this structure, the device can achieve responsivities as high as 3.75 mA/W and 1.58 mA/W for wavelengths of 1310 nm and 1550 nm, respectively. These insights can enhance efficiencies and lower cost in optical communication systems.

1. Introduction

Surface plasmons (SPs), a coherent oscillation of electrons, which can be excited in metal by the electromagnetic wave [1], can promote the ability to trap light [2] by increasing light-matter interaction of the diffraction limit. Nowadays, they have been applied in numerous fields including sub-diffraction-limited imaging [3], photovoltaic devices [4] and environmental sensors [5]. Due to the mechanism of SPs, metal can be excited by the incident light. After excitation, surface plasmons would decay either radiatively into re-emitted photons or nonradiatively by forming hot electrons [6]. The nonradiative decay of plasmons, which can generate hot electrons, can be used for hot-electron photodetection [7]. Hot-electron photodetectors are formed by placing the metal nanoelectrodes in contact with a semiconductor [8], forming a Schottky barrier. Hot electrons generated in metal nanoelectrodes travel to the metal-semiconductor interface and cross Schottky barrier, resulting in photocurrent. Consequently, the bandwidth of photodetectors can be decided by the Schottky barrier height rather than the bandgap of the semiconductor. This allows hot-electron photodetectors to be exploited for optical communications without bonding or extending low-bandgap semiconductors on silicon [9,10], which can reduce the cost of optical communications.

Recent years, hot-electron photodetection has been investigated by many groups. Naomi J. Halas et al. accomplished an active optical antenna device of fabricating Au resonant antennas on n-type Si substrate, which achieved tunable peak response at wavelength range of 1250–1600 nm in the order of μA/W [11].

Moreover, the responsivity of silicon-based hot-electron photodetectors in communication band has been greatly improved via pyramid [12], embedded [13], chiral metamaterial [14] nanoelectrode structure. These researches have greatly improved the responsivity of hot-electron photodetectors for optical communications. Generally, the responsivity of hot-electron photodetectors is determined by optical absorption and hot-electron collection. Current researches mostly focus on enhancement of optical absorption.

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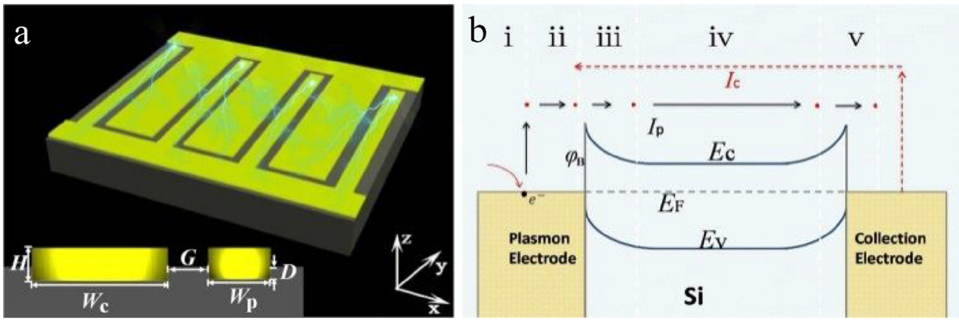

Fig. 1. (a) Schematic of the embedded asymmetric nano-gap hot electron photodetectors. W_p and W_c are the widths of the plasmon electrodes and the collection electrodes, respectively, H is the height of electrodes, G is the electrode gap, D is the embedding depth of electrodes. (b) Band diagram of the device. The photocurrent is generated by five consecutive steps.

However, hot-electron collection is also a critical factor for photoresponse capability. Hence, realizing effective hot-electron collection will provide further opportunities for the development of hot-electron photodetectors.

In our recent researches, a device based on asymmetric nano-gap electrodes is demonstrated to improve responsivity [15] by reducing the traveling length of hot electrons to the order of sub-micron. In this paper, we present a silicon based hot-electron photodetector with embedded asymmetric [16] plasmonic nano-gap electrodes. It realizes a higher responsivity due to the efficient collection of hot electrons. This device has a great potential to replace costly InGaAs and germanium detectors in the field of optical communications.

Fig. 1(a) shows an embedded asymmetric nano-gap photodetector based on metal-semiconductor (Au-Si) Schottky barrier [17–19]. Asymmetric gold electrodes are embedded into the silicon substrate. The narrow ones are plasmon electrodes and the wide ones are collection electrodes. The devices can be fabricated by the electron beam lithography [20], etching, the electron beam evaporation and the lift-off process [21]. Excited by incident light of polarization in the x direction, the nonequilibrium photocurrents of plasmon

electrodes and collection electrodes, I_p and I_c, will be generated in the device. When the width of collection is 1000 nm, hot electrons induced in the plasmon electrodes are much more than those in the collection electrodes. The net current I can be expressed as $I=I_p$-I_c [15], and I_c can be ignored in this paper. Thus, this device can work without plus bias voltage due to the asymmetric structure.

2. Computational methods

It can be observed from Fig. 1(b) that the process of generating photocurrent consists of five steps. Firstly, when light with frequency ν incidents on the Au electrodes, plasmon resonance will be excited and a large number of hot electrons will be produced. The initial energy of the hot electrons can be calculated as $E_0 = h\nu$, where h is Planck's constant. Secondly, hot electrons arrive at the Au-Si interface, and their kinetic energy can be expressed as $E_k = E_0 e^{-s/L}$, where s is total distance of hot electron traveling, L is the mean free path of the electrons. Thirdly, hot electrons cross the Schottky barrier with a certain number of probability [22]. Then, a part of survival hot electrons travel across the gap in the Si substrate. Finally, hot electrons will reach collection electrodes and be collected.

The relationship between kinetic energy and momentum of the hot electrons arriving at Au-Si interface in Au electrodes can be expressed by:

$$E_k = \frac{\hbar^2}{2m_e^*} k_{Au}^2 \tag{1}$$

Where $\hbar$ is reduced Planck's constant, m_e^* is the effective mass of the electron, k_{Au} is the total momentum of the hot electron at Au-Si interface in plasmon electrodes, which is given by:.

$$k_{Au}^2 = k_{Au,x}^2 + k_{Au,z}^2 \tag{2}$$

where $k_{Au,x}$ and $k_{Au,z}$ are the momentums of the hot electron in plasmon electrodes in the x and the z directions, respectively.

Once the hot electron injects into the Si substrate, both kinetic energy and momentum would change. The kinetic energy can be calculated as:

$$E_k - \varphi_B = \frac{\hbar^2}{2m_e^*} k_{Si}^2 \tag{3}$$

Here, φ_B is the height of Schottky barrier. Similarly, k_{Si} is the total momentum of hot electrons at Au-Si interface in Si substrate:

$$k_{Si}^2 = k_{Si,x}^2 + k_{Si,z}^2 \tag{4}$$