Hydrodynamic Analysis and Responsivity Improvement of a Metal/Semiconductor/Metal Plasmonic Detector

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Abstract

Characteristic improvements of photon/plasmon detectors have been the subject of several investigations in the area of plasmonic integrated circuits. Among different suggestions, silicon-based metal-semiconductor-metal (MSM) waveguides are one of the most popular structures for the implementation of high-quality photon/plasmon detectors in infrared wavelengths. In this paper, an integrated silicon-germanium (SiGe) core MSM plasmon detector is proposed to detect $\lambda = 1550$ nm with internal photoemission mechanism. Performance characteristics of the new sub-micron device are simulated with a simplified hydrodynamic model. In a specific bias point ($V = 3$ V and the incident optical power of 0.31 mW), the output current is 404.3 $\mu$A (276 $\mu$A detection current and 128.3 $\mu$A dark current), responsivity is 0.89 A/W, and the 3-dB electrical bandwidth is 120 GHz. Simulation results for the proposed plasmon detector, in comparison with the empirical results of a reported Si-based MSM device, demonstrate considerable responsivity enhancement.

Keywords Plasmonics · Detector · Internal photoemission · SiGe · Simplified hydrodynamic model

Introduction

There are a plethora of researches on finding proper materials for detection of different electromagnetic wavelengths from infrared (IR) to ultraviolet (UV) [1]. However, silicon-based detectors are more desirable because of fabrication technology considerations. The energy bandgap ($E_g$) of silicon (Si) is 1.08 eV at room temperature. It means that this material can generate electron-hole pairs (EHP) in visible wavelengths. In order to extend the detection wavelengths of Si to IR region, internal photoemission (IPE) mechanism can be replaced instead of EHP. Nevertheless, the detection efficiency of the IPE mechanism is much lower than that of the EHP and plasmons are the key to ameliorate the effect of this limitation [2]. Plasmon detectors have a higher absorption rate and are more sensitive to polarization, angle, and wavelength of the incident electromagnetic waves [2]. These detectors are commonly made from a metal, which provides the coupling condition of photons to plasmons, and a semiconductor in Schottky junction configuration. Based on the metal architecture in plasmonic detectors, these devices have a wide variety of structures [3–6]. Among those, waveguide plasmonic detectors have particular importance because of CMOS compatibility and integration capability with plasmonic integrated circuit elements [7, 8]. With this in mind, improving characteristics of Si-based waveguide plasmon detectors has been the subject of several investigations [9–11].

Among different high-quality plasmon detectors, initially, we focused on a germanium (Ge)–based waveguide detector, reported in ref. [12], with significant detection responsivity. However, this detector has some drawbacks compared with the Si-based structures. For instance, the EHP mechanism of IR detection in Ge-based devices reduces the electrical bandwidth (BW) of the detector. It is due to that the switching speed of bipolar devices is controlled by the recombination speed of their minority injected carriers, while in the IPE mechanism, the device’s switching speed is controlled by injection of hot carriers over the Schottky barrier and this time constant is much lower than the former [13]. Moreover, the higher expense of Ge fabrication technology is another negative point compared with Si. Considering these characteristics, we want to utilize a middle state between Si and Ge to benefit from features of both semiconductors.

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In this paper, a Si-SiGe-based MSM waveguide has been proposed as an IR plasmon detector. The operation of this sub-micron device is analyzed with a simplified hydrodynamic (SHD) model to apply the non-local transport effects, such as carriers’ temperature gradient associated with the hot carrier generation of IPE mechanism. We have utilized the reported structures of [11, 12] as the basis of our design procedure. In the proposed detector, the lower bandgap of SiGe improves detector’s responsivity in comparison with the initial IPE-based Si core plasmon detector [11], and the higher detection speed of IPE mechanism (due to its unipolar operation and the Schottky junction characteristics) increases the BW of the proposed detector compared with the Ge-based structure [12]. The process of this paper is as follows: the physical structure of the proposed detector is introduced in the Device Physical Structure section. Then, device analysis and simulation method are discussed in the Device Analysis and Simulation Method sections respectively. Results of simulations are presented in the Results section. Finally, the achievements of this work will be summarized in the Conclusion section.

Device Physical Structure

The physical structure of the proposed plasmon detector is presented in Fig. 1. This waveguide has a lightly p-doped Si-SiGe core sandwiched between titanium (Ti) and gold (Au) layers. The photonic to plasmonic mode converter in this detector is a tapered waveguide configuration same as [11] and is not shown in Fig. 1. Physical parameters of the detector are listed in Table 1. In this structure, carriers flow through the narrower region of the semiconductor core which is considered as an active region (height≈275 nm) in Fig. 1a. The maximum height of the SiGe layer is dependent on Ge mole fraction (x) and is determined for x = 5%, 10%, and 13% in Table 1 [14].

In this structure, the SiGe region has lower $E_g$ in comparison with Si that provides a channel for carriers. Moreover, the lower bandgap of SiGe reduces the height of the Schottky barrier for holes and enhances the dark and detection currents of the detector. In order to compensate the increased dark current, this detector can be imported in a balanced structure, as described in our previous work [15], to isolate the output of the detector from the dark current.

Device Analysis

Electromagnetic Analysis

Mode analysis of the proposed Au/Si-SiGe/Ti plasmon detector has been done in LUMERICAL simulator for different Ge mole fractions (x). The simulated device structure is shown in Fig. 2. This structure consists of a photonic and a tapered waveguide that converts photonic modes to plasmonic ones.

The propagation modes of the photonic and plasmonic waveguides with $x = 0, 10, 30\%$ are shown in Fig. 3. The height of the SiGe layer remains constant (50 nm as shown in Fig. 1b) for all cases to provide a better condition for comparing the x variation effect. As can be seen, by raising the Ge mole fraction, the confinement of the electrical field will increase that causes the enhancement of plasmon loss rate and improving the hot carrier generation in the SiGe region. Moreover, the length of Si-SiGe core MSM can be set much

| Type/dope (cm$^{-3}$) | Width (nm) | Height (nm) | Length (μm) |
|----------------------|------------|-------------|-------------|
| Si core P-type/10$^{15}$ | W = 75 | H = 275 | L = 5 |
| SiGe core P-type/10$^{15}$ | $W = 75$ | $200$ (x = 5%) | $L = 5$ |
| | | $50$ (x = 10%) | |
| | | $40$ (x = 13%) | |
| Metals – | t = 40 | – | L = 5 |

Table 1 The physical structure of the proposed plasmon detector

Fig. 1 a Physical structure and dimensions of the proposed plasmon detector. b Magnified active region and biasing circuit of the detector
lower than the corresponding structure with Si core that reduces the total area of the proposed detector and can create a positive effect for decreasing the dark current. However, in the following simulations, we consider the dimensions of Si-SiGe device same as the initial Si core structure to have a platform for studying other aspects of SiGe existence in characteristics of the proposed detector.

In another part of LUMERICAL simulations, the coupling coefficient \( A \) of the tapered waveguide is calculated by dividing the spatial integral of plasmonic wave power into the spatial integral of the photonic wave which is determined as 4\% and 3\% for Si and SiGe core MSMs respectively. These coupling coefficients will be used in the equation of IPE model in the Current Analysis section for determining the detection current.

### Energy Band Diagram

The energy band diagram of the Au-Si-Ti and Au-SiGe-Ti are shown in Fig. 4. The Schottky barriers for electrons on each side of this MSM structures can be calculated by \( \Phi_{\mathrm{bn}} = W - X \), where \( W \) is the metal’s work function (\( W_{\text{Au}} = 5 \) eV and \( W_{\text{Ti}} = 4.8 \) eV) and \( X \) is the electron affinity of the semiconductor that considered as 4.2 eV for Si and SiGe [11, 15]. Since a
Schottky diode operates based on majority carriers, in p-doped core MSM waveguide, all calculations should be done on holes. The Schottky barrier for electrons can be converted to holes by $\phi_B = E_g - (W - X)$ where $E_{g_{Si}} = 1.08$ eV and for SiGe can be calculated as \[ E_g = 1.08 + x(0.945-1.08)/0.245 \quad \text{for} \quad x \leq 0.245 \] \[ \phi_B = E_{g_{Si}} - x(0.945-1.08)/0.245 \] \[ (1) \]

The room temperature Schottky barrier heights for holes at Au-Si, Au-SiGe, Ti-Si, and Ti-SiGe interfaces are shown in Fig. 4. To extend these calculations into lower temperatures, we use the Eq. (2) to determine bandgap energy dependency to temperature \[ E_g(T) = E_g(0) - \frac{\alpha T^2}{(T + \beta)} = E_g(300K) + \alpha \left( \frac{300^2}{300 + \beta} - \frac{T^2}{T + \beta} \right) \] \[ \text{where} \alpha \quad \text{and} \beta \quad \text{are the material dependent coefficients that are} \] \[ 4.73 \times 10^{-4} \text{eV/K and 636 K for Si [17] and for SiGe are as follows [18]} \] \[ \alpha = (\alpha_{Si} + x(\alpha_{Ge} - \alpha_{Si})) \times 10^{-4} \] \[ = (4.73 + x(4.77 - 4.73)) \times 10^{-4} \text{eV/K} \] \[ \beta = \beta_{Si} + x(\beta_{Ge} - \beta_{Si}) = 636 + x(235 - 636) \text{K} \] \[ (3) \]

Detailed energy band diagram of Fig. 4 is sketched in Fig. 5a. According to this diagram, Au contact should be connect-
ed to a higher potential than the Ti side to compensate the built-in voltage ($V_{bi}$) arising from the Schottky barrier difference between two junctions. Under an appropriate biasing condition, the energy diagram of Fig. 5a changes into Fig. 5b. Under this condition, the Schottky barrier lowering effect changes the height of the barriers. The Schottky effect is the image force–induced lowering of the potential energy for charge carrier emission and is proportional to applied voltage according to the following Eq. (18).

\[ \Delta \phi_B = \sqrt{\frac{q V_{app}}{4 \pi \varepsilon_0 W}} \] \[ (4) \]

Here, $V_{app}$ is the applied voltage, $q$ is the elemental charge, $\varepsilon_0$ is the semiconductor’s permittivity (which is 11.8 for Si and 11.8 + 4.2x [18] for SiGe), and $W$ is the core width in the MSM structure. By applying this effect, in the forward biased junction, the barrier height is slightly larger and for reverse bias, the barrier height becomes slightly smaller than the zero bias condition [17] (e.g., $\Delta \phi_B = 0.0351$ eV at $V_{app} = 2$ V).

**Current Analysis**

In Fig. 5a, surface plasmon polaritons (SPPs) propagate along both interfaces [19]. According to Beer’s law ($\alpha = 2\omega/c \left[ \text{Im} \left( \varepsilon_r \right) / 2 \right]^{0.5}$ where $\alpha$ is the attenuation coefficient in metal, $\varepsilon_r$, and $\omega$ is the metal’s relative permittivity and angular frequency of photons and $c$ is the speed of light), plasmon absorption is proportional to imaginary part of metal permittivity at desired wavelength [19]. The relative permittivity of gold and titanium can be calculated by the Drude-Lorentz model [20] as –
93.06 + 11.11i and −4.87 + 33.7i at \( \lambda = 1550 \) nm respectively. Considering these data, the titanium side has a prominent role in plasmon absorption (or hot carrier generation); however, based on the energy diagram of Fig. 5b, the applied voltage causes the flow of hot holes from gold to titanium contact and creates an electrical current in the same direction. In this section, the current relations of an MSM structure with energy diagram of Fig. 5 will be described at first. Then, the generation of hot holes in the Au side (IPE detection mechanism) will be described which should be imported in current relations for device simulation in detection mode.

**MSM Current (Dark Current)**

In this paper, the operation of the proposed sub-micron MSM plasmon detector is analyzed with a simplified hydrodynamic (SHD) model [21, 22]—which solves the continuity equations for the carrier’s temperatures—to apply the effect of carriers’ temperature gradient associated with the hot carrier generation of IPE mechanism. The derivation of this model, like as drift-diffusion (DD) model, started from the Boltzmann transport equations [22] and compared with the DD model, two additional independent variables, \( T_n \) and \( T_p \), the temperature of electrons and holes—in addition to lattice temperature \( (T_L) \)—are considered in this model that makes the transport parameters (like mobility, diffusion coefficients) temperature-dependent. The SHD model equations for holes consist of [22]

\[
\begin{align*}
\text{div} S_p &= \frac{1}{q} \mathbf{J}_p - \nabla \cdot \mathbf{W}_p - \frac{3K}{2} \frac{\partial}{\partial t} (pT_p) \\
\mathbf{J}_p &= -qD_p \nabla p - q\mu_p \mathbf{E} - qD_p^T \nabla T_p \\
\mathbf{S}_p &= -K_p \nabla T_p - \left( \frac{K_0}{q} \right) \mathbf{J}_p T_p 
\end{align*}
\]

(5)

where \( S_p \) is the hole’s energy flux density, \( \mu_p \) is the hole mobility, \( E \) is the electric field, \( K \) is the Boltzmann constant, \( D_p = \mu_p K T_p / q \) is the hole’s thermal diffusivity, \( p \) is the hole’s concentration, and \( \psi \) is the electrostatic potential. The three components of \( J_p \) equation are referred as particle diffusion, particle drift, and thermal diffusion, respectively [22]. Other parameters of equation sets of (5) are defined as follows [21]:

\[
K_p = q\mu_p \left( \frac{K}{q} \right)^2 \Delta_p T_p \\
\Delta_p = \delta_p \left[ \frac{7}{2} F_0 + 5/2 \left( \eta_p \right) - \frac{5}{2} F_0 + 3/2 \left( \eta_p \right) \right] \\
\delta_p = \frac{\mu_{2p}}{\mu_p}, \quad \mu_{2p} = 5/2 \mu_p \left( \frac{F_0 + 3/2 \left( \eta_p \right)}{F_0 + 1/2 \left( \eta_p \right)} \right) \\
\eta_p = \left( \frac{p}{N_V} \right)^{1/2} \\
N_V = \left( \frac{2\pi m_p K T_p}{h^2} \right)^{1.5} = \left( \frac{T_p}{300} \right)^{1.5} N_V(300) \\
D_p = \left( \frac{\mu_{2p}}{2} \mu_p \right) \left( \frac{K}{q} \right)
\]

where \( F \) is the Fermi-Dirac integral and \( N_V \) is the hole’s effective density of states. The \( W_p \) in Eq. (5) is the loss rate that includes physical mechanisms by which carriers exchange energy with the surrounding lattice environment and is considered as follows [21]:

\[
W_p = \frac{3}{2} \rho \left( T_p - T_L \right) / \tau_h
\]

(7)

That \( \tau_h \) is the hole’s energy relaxation time in the semiconductor. The holes mobility in previous equations is dependent on temperature and electrical field according to [18].

\[
\mu_p(T) = \mu_p(300) \sqrt{\frac{T_L}{300}}
\]

(8)
\[ \mu_p(E) = \frac{\mu_{p0}}{\sqrt{1 + \left( \frac{\mu_{n0}E}{V_{app}} \right)^2}} \] (9)

Where \( V_{sat,p} \) is the hole’s saturation velocity, and \( \mu_{p0} \) and \( \mu_{n0} \) are the room temperature mobility and low field mobility respectively which are determined based on semiconductor’s material and its doping level.

The material parameters in Eq. (5–9) are for Si and SiGe in simulations of the proposed device. The Si parameters are reported in various resources, and some SiGe parameters are considered similar to Si especially in low Ge mole fractions. However, a number of SiGe parameters have different amounts. For instance, the \( N_y \) and holes mobility of SiGe are 0.23 [23] and 1.25 [24] times the Si values respectively for \( x = 10\% \).

Eventually, solving SHD equations needs a boundary condition to determine \( p \) and \( \psi \). The boundary condition in the proposed MSM detector is Schottky contact equations. The current of a Schottky junction is divided into thermionic and tunneling parts which are shown for electron carriers in Fig. 6.

The thermionic component of current in a Schottky junction from metal to semiconductor region is [17]

\[ \bar{J}_{sp} = A_p^* T_L^2 \exp \left( -\frac{qF_B}{kT_L} \right). \] (10)

Where \( A_p^* \) is effective Richardson’s coefficient for holes, and \( T_L \) is the hole’s temperature which sets equal to lattice temperature on the contacts. Tunneling component of current in a Schottky junction can be described by [25]. (In the following equations, tunneling of electrons is described because of its simpler vision; however, these equations will be adapted to holes at the end of this section.)

\[ J_T = \frac{A^* T_L^2}{K} \int_{E}^{\infty} \Gamma'(E') \ln \left[ 1 + \frac{f_s(E')}{f_m(E')} \right] dE'. \] (11)

Where \( f_s(E) \) and \( f_m(E) \) are the Maxwell-Boltzmann distribution functions in the semiconductor and metal, \( E \) is the carrier energy, and \( \Gamma'(E) \) is the tunneling probability. To obtain the localized tunneling rate \( \Gamma(y) \), eq. (11) is imported in \( G_T = \frac{\nabla J_T}{q} \) and yields [26]:

\[ G_T = \frac{A^* T_L^2}{K} \Gamma(y) \ln \left[ 1 + \frac{n}{\gamma_n N_c} \exp\left[-\left(E_c - E_{FM}\right)/kT\right] \right] \] (12)

Where \( E \) and \( n \) are the local electric field and local electron concentration, \( N_c \) is the local conduction band density of states, \( \gamma_n \) is the local Fermi-Dirac factor, \( E_{FM} \) is the Fermi level in the contact, and \( E_c \) is the local conduction band edge energy which is related to \( V_{app} \) according to Fig. 6 and can be written as

\[ E_c(y) = \frac{\Phi_{BN-Au} - \Phi_{BN-Ti} - qV_{app}}{W} + \Phi_{BN-Ti}. \] (13)

The tunneling probability \( \Gamma(y) \) in Eq. (12) can be determined by assuming this linear variation of conduction band energy \( E_c \) as follows [26]:

\[ \Gamma(y) = \exp \left[ -\frac{4\sqrt{2mv_0}}{3h} (E_{FM} + \Phi_{BN-Ti} - E_c(y))^2 \right] \] (14)

Here, \( m \) is the electron effective mass for tunneling and \( h \) is reduced Planck’s constant. Based on Eq. (13), in a specific “\( y \)” by increasing the applied voltage, \( E_c(y) \) will decrease which causes enhancement of tunneling probability according to Eq. (14). Similar expressions of the above equations exist for holes by replacing \( E_c(y) = E_n(y) - E_g \), hole’s average effective mass, \( \Phi_{BN} \) etc. instead of corresponding parameters in Eqs. (11)–(14).

IPE Model

After excitation of SPPs in a metal-semiconductor interface, the absorption of plasmons can occur in each side of this interface according to the level of photons’ energy \( (E = h; \ h \) is Planck’s constant and \( v \) is optical frequency). For \( h > E_g \), plasmons absorb in semiconductor side and generate electron-hole pairs (EHP). However, IR photons by free space wavelength of 1550 nm (\( h = 0.8 \) eV) have lower energy than silicon bandgap, so excited plasmons absorb in the metal side and detection occurs based on IPE mechanism. IPE can be described as a 3-step process [2]: (1) The generation of hot carriers by absorption of photons/plasmons in the metal side, (2) transmission and scattering of hot carriers toward semiconductor interface, (3) emission of hot carriers from Schottky
barrier and creating detection current. This 3-step process can be described by a semi-classical model [27]. According to this model, internal quantum efficiency is calculated by

$$\eta_i = \frac{I_p}{q} \frac{S_{abs}}{h \nu} = \frac{1}{2} \left(1 - \sqrt{\frac{\Phi_B}{h \nu}}\right)^2.$$  \hspace{1cm} (15)

Where $I_p$ is photocurrent and $S_{abs}$ is absorbed optical power, which is converted to incident optical power by $S_{abs} = A S_{inc}$. Therefore, photodetection current in a Schottky interface was obtained as follows:

$$I_p = q \frac{A S_{inc}}{2h \nu} \left(1 - \sqrt{\frac{\Phi_B}{h \nu}}\right)^2.$$ \hspace{1cm} (16)

This current should be imported in the dark current of the gold to semiconductor junction (Eq. (10)) to determine the total boundary current of the SHD model for simulation of the proposed MSM detector in the illumination mode. This process will be described in Simulation Method section.

**Signal and Noise Analysis**

Operating speed limitation of the MSM plasmon detector is relevant to various phenomena, such as hot carrier lifetime in metals ($\tau_{hc}$), carriers drift time through the semiconductor layer ($\tau_{dr}$), and RC time constant ($\tau_{RC}$) [11], according to the following relation:

$$f_{3dB} = \frac{1}{2 \pi \sum \tau}.$$ \hspace{1cm} (17)

The hot carrier lifetime in Au is considered as 30 fs [28]. Due to the narrow thickness (75 nm) of the semiconductor layer, the drift time of carriers is specified by considering the saturation velocity. The hole’s saturation velocities are considered as $0.8 \times 10^7$ cm/s and $0.6 \times 10^7$ cm/s for Si and SiGe ($x = 10\%$) respectively [29]. Finally, the RC time constant of the MSM junction is determined by estimating an equivalent parallel plate capacitor ($C$) with $5 \mu m \times 275$-nm metal area across $W = 75$ nm Si core which leads to a capacitance equal to 1.9 fF. However, in Si-SiGe core MSM, the SiGe region is a channel for current due to its lower energy bandgap and as it is shown in Fig. 7, the effective area will reduce to $L \times H_{SiGe} = 5 \mu m \times 50$ nm (for $x = 10\%$). Moreover, the relative permittivity of SiGe is [18]

$$\varepsilon_{Si} = 11.8 + 4.2x.$$ \hspace{1cm} (18)

Consequently, $C_{SiGe} = 0.36$ fF for $x = 10\%$. The load resistance is considered as $R = 50 \Omega$ for both MSM devices.

Given these points, the 3-dB bandwidths of the Si and Si-SiGe core MSM detectors are calculated as 149 GHz and 120 GHz respectively which show a 19% reduction for the proposed device in comparison with the initial Si core detector because of lower saturation velocity of holes in SiGe.

Another key characteristic of a detector is the signal-to-noise ratio (SNR) which can be determined by considering the shot, thermal, and dark current noise sources as follows [30]:

$$\frac{S}{N} = \frac{I_{det}^2}{2qB(I_{det} + I_{dark}) + \frac{4KTB}{R} + i_{dark}^2}.$$ \hspace{1cm} (19)

Where $B$ is the modulation frequency of the input signal. This characteristic will be calculated in the Results section.

**Simulation Method**

Dark current simulations of the proposed MSM plasmon detector have been done by solving the Eqs. (5)–(14) of the Device Analysis section. In the detection mode, we use an indirect method for importing detection current (Eq. (16)) in Schottky boundary condition of SHD calculations. As it was mentioned before, the hole temperatures in contacts are set equal to the lattice temperature and then SHD model considers continuity equations for the carrier temperatures. In the detection mode, the average energy of carriers increases by absorbing plasmon energy and the generation of hot carriers. Another way to enhance carrier energy (and as a result, improving thermionic emission) is increasing the operational temperature. With this in mind, we use an effective temperature concept to create the detection condition in the Schottky current equation (Eq. (10)) and generate hot carriers by...
increasing the lattice effective temperature ($T_{\text{eff}}$) (boundary condition for temperature).

For determining the effective temperatures, the detection currents are calculated for the different incident optical powers (Eq. (16)). Then, Eq. (10) sets equal to these currents and $T_{\text{eff}}$ is calculated for each optical power. The calculated effective temperatures for a number of incident optical powers are listed in Table 2. These temperatures have earned a maximum ± 5-K variations during simulations to create a perfect linear behavior in the responsivity curves but remained constant for each device at different voltages. These calculations have been done on Au-Si junction with $\phi_{Bp} = 0.28$ eV, $A_p = 30$ A/cm$^2$/K$^2$ and $\lambda = 1550$ nm. These effective temperatures remain constant for simulation of Au/Si-SiGe/Ti structure in each incident optical power. Figure 8 shows the temperature variation results of SHD model for two lattice temperatures of 250 K and 312 K.

In order to verify the validity of the mentioned method, the fabricated structure reported in [11] is simulated and the results are compared with the reported empirical curves in Fig. 9. As can be seen, there is a proper agreement between simulated and reported results. Similarities between the structure of the proposed device of this work and reported device of [11] allow us to apply the discussed theories for simulation of the proposed device in the same biasing condition.

### Table 2  Calculated effective lattice temperatures for different incident optical powers

| $S_{\text{inc}}$ (dark mode) | 100 $\mu$W | 150 $\mu$W | 200 $\mu$W | 250 $\mu$W | 310 $\mu$W |
|-------------------------------|------------|------------|------------|------------|------------|
| $T_{\text{eff}}$              | 250 K      | 277 K      | 290 K      | 299 K      | 306 K      | 312 K      |

The current-voltage characteristic of the proposed MSM plasmon detector is presented in Fig. 10. The operational condition of this I–V curve is similar to Fig. 9, and as can be seen, the dark and detection currents are 21 and 10 times more than the corresponding values of the initial detector respectively. This dark current enhancement is the cost of increasing the detection current of the plasmon detector.

![Fig. 8 The temperature variation results of SHD model for two lattice temperatures](image)

![Fig. 9 Comparison of simulation results with empirical curves [11]. Both experiment and simulation results belong to Au-Si-Ti detector](image)

![Fig. 10 I–V characteristic of the proposed MSM plasmon detector](image)

Results

The current-voltage characteristic of the proposed MSM plasmon detector is presented in Fig. 10. The operational condition of this I–V curve is similar to Fig. 9, and as can be seen, the dark and detection currents are 21 and 10 times more than the corresponding values of the initial detector respectively. This dark current enhancement is the cost of increasing the detection current of the plasmon detector.
The responsivity ($R$) of a detector is defined as the slope of output current versus optical input power characteristic, which is plotted at three different bias voltages for both Si core and Si-SiGe core devices in Figs. 11 and 12 respectively. The responsivity of the proposed detector has $\times 10.3$, $\times 10$, and $\times 8.5$ growth at $V = 1, 2, 3$ V respectively.

The effect of Ge mole fraction variations in the output currents of the proposed plasmon detector is plotted in Fig. 13 for $x = 5\%$, 10\%, and 13\% with maximum allowable height for SiGe layer ($H_{SiGe} = 200, 50, 40$ nm respectively [14]). As can be seen, the dark and detection currents increase very fast by raising the Ge mole fraction.

Finally, in order to evaluate the performance of the proposed device, different parameters of both structures are summarized in Table 3 for $x = 10\%$, $S_{inc} = 0.31$ mW, and $V = 3$ V. In Si-SiGe core MSM detector, the dark current noise has the dominant role in comparison with other noise sources and reduces the SNR of the proposed detector. However, by importing these MSM detectors in a balanced structure [15] and eliminating the dark current from the output, the higher detection current of Si-SiGe core structure increases the SNR of the proposed detector in the balanced configuration.

**Table 3** Comparison of simulated parameters for Si-SiGe core and Si core MSM plasmon detectors (at $V = 3$ V and $S_{inc} = 0.31$ mW)

|                  | Si-SiGe core proposed detector | Si core initial detector |
|------------------|--------------------------------|--------------------------|
| Dark current     | 128.3 $\mu$A                  | 6.07 $\mu$A              |
| Output current in detection mode | 404.3 $\mu$A | 39.74 $\mu$A |
| Responsivity     | 0.89 A/W                       | 0.10 A/W                 |
| Elec. BW         | 120 GHz                        | 149 GHz                  |
| SNR              | 6.64 dB (at 120 GHz)           | 11.51 dB (at 149 GHz)    |
| SNR in a balanced configuration ($I_d = 0$) | 38.24 dB | 18.64 dB |
Conclusion

In this paper, an IPE-based Si-SiGe core MSM plasmonic detector is proposed and theoretically analyzed. The proposed detector has higher detection current and responsivity compared with the Si-based structure [11]. However, these advantages are in a trade-off with dark current noise—which can be compensated in a balanced structure [15]—and electrical modulation bandwidth. On the other hand, in comparison with a Ge-based detector [12], the proposed device has lower responsivity (because of using IPE mechanism instead of EHP) and better dark current and BW characteristics. However, the Si-SiGe core structure of this work has been compared with the Si-core structure due to the same detection mechanism.

The performance of the new device is theoretically investigated with a simplified hydrodynamic model. In a specific bias point ($V = 3$ V and $S_{inc} = 0.31$ mW), the bandwidth is 120 GHz and SNR is 6.64 dB that have 19% and 42% reduction respectively. However, the output current is 404.3 µA and responsivity is about 0.89 A/W that have improved 10 and 8.9 times compared with the initial Si core plasmonic detector values respectively. These properties suggest a responsive plasmonic detector that can create the same output photocurrent under a lower illuminating power in comparison with conventional plasmonic detectors.

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