Hot electron photodetection with spectral selectivity in the C-band using a silicon channel-separated gold grating structure

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Abstract
Photodetection based on hot electrons is attracting interest due to its capability of enabling photodetection at sub-bandgap energies of semiconductor materials. Si-based photodetectors incorporating hot electrons have emerged as one of the most widely studied devices used for near infrared (NIR) photodetection. However, most reported Si-based NIR photodetectors have broad bandwidths with responsivities that change slowly with the target wavelength, limiting their practicality as spectrally selective photodetectors. This paper reports a Si channel-separated Au grating structure that exhibits the spectrally selective photodetection in the C-band (1530–1565 nm). The measured responsivity of the structure drops from 64.5 nA mW$^{-1}$ at 1530 nm to 19.0 nA mW$^{-1}$ at 1565 nm, representing a variation of 70.5% over the C-band. The narrowband, ease of tuning the resonant wavelength, and spectral selectivity of the device not only help bridge the gap between the optical and electrical systems for photodetection but are also beneficial in other potential applications, such as sensing, imaging, and communications systems.

1. Introduction
Plasmonic nanostructures have received extensive attention due to their ability to increase the harvesting of incident light from free space and concentrate electromagnetic energy to nanoscale volumes through the excitation of surface plasmons (SPs). With this outstanding property, plasmonic nanostructures have been widely used to enhance the performance of optoelectronic devices, such as photocatalysis devices [1, 2], solar energy harvesting devices [3, 4], lasing devices [5, 6], imaging devices [7], monitoring devices [8], and photodetectors [9–14]. SP-based photodetectors generally have higher external quantum efficiencies and responsivities than conventional photodetectors because of the enhanced light absorption and the ability to generate hot electrons through the nonradiative decay of SPs [15, 16]. This has led to them also being referred to as hot electron photodetectors. In hot electron photodetectors, hot electrons with energies exceeding the barrier height can cross the barrier before thermalization and be injected into the conduction band of the semiconductor, resulting in a photocurrent that can be detected with an external circuit. The most frequently discussed configurations of hot electron photodetectors are the metal-insulator-metal (MIM) configuration, metal-semiconductor (MS) configuration and metal-semiconductor-metal (MSM) configuration. In the MIM configuration, one of the biggest drawbacks comes from the low efficiency of hot electron generation and propagation across the high M/I barrier [16, 17]. Due to the high M/I barrier, the probability of hot electrons excited by low-frequency photons crossing the barrier is low, and this limits the photodetection in the ultraviolet (UV) and visible ranges [16, 18–20]. The emergence of MS and MSM configurations has resolved the high barrier problem as they have a relatively lower barrier height compared to the MIM configuration. Hot electron
photodetectors with these two configurations overcome the native limitations from the bandgap of semiconductors, enabling the selective detection of photons whose energy \((\hbar \nu)\) is higher than the barrier height \((\phi_b)\) but lower than the bandgap \((E_g)\) of a semiconductor (i.e., \(\phi_b < \hbar \nu < E_g\)). Therefore, hot electron photodetectors with MS and MSM configurations are capable of achieving photodetection at sub-bandgap energies of semiconductors, extending the photodetection to the near infrared (NIR) range \([12, 13, 21, 22]\).

In hot electron photodetectors with MS configurations, such as antennas \([21, 22]\), metamaterial perfect absorbers \([23]\), Au gratings \([24, 25]\), nanowires \([26-28]\), waveguides \([29, 30]\), and deep-trench/thin-metal structures \([31]\), hot electrons are generated in a single metallic layer and produce a unidirectional photocurrent. In MSM configurations, the semiconductor component is commonly sandwiched between two opposite metallic layers, such as top/bottom or left/right metallic layers, resulting in hot electrons being generated in both metals and transporting in opposite directions. A net photocurrent in the MSM configuration can be generated by creating an asymmetrical absorption in the two metallic layers by using different structures or different metals. Another way to obtain a net photocurrent is to apply a bias voltage to produce asymmetrical Schottky junctions. An increasing number of hot electron photodetectors with MSM configurations have been reported in recent years, including Au nanodipole arrays \([32]\), waveguide-based Al/p-Si/Cu structure \([33]\), and conformal Au/ZnO/Au grating \([34]\). In both MS and MSM configurations, the grating-based structures usually offer strong light confinement and the resonant wavelength is readily tuned over a wide range by adjusting the period of the structure or the incident angle of light. This paper proposes a Si channel-separated Au grating structure (MSM configuration) by integrating a subwavelength Au grating with Si channel arrays. The structure takes advantage of the MSM configuration and combines the features of plasmonic gratings with the SP-induced hot electrons for spectrally selective photodetection at telecommunication wavelengths. The insights gained from this study can help aid the realization of ultracompact and efficient hot electron photodetectors.

2. Experiment and simulation

2.1. Schematic diagram of the structure and the fabrication process

Figure 1 (a) shows a schematic diagram of the proposed Si channel-separated Au grating structure, which consists of an n-type Si substrate and Au slabs separated by Si channels. A bias voltage is applied on the leftmost and rightmost Au slabs of the grating. The cross-section of one periodic unit of the structure is shown in figure 1(b). The width \((w)\) and height \((h)\) of the Si channel, the thickness of the Au slab \((t)\), the period of the structure \((p)\), and the incident angle \((\theta)\) of light are all indicated. A linear polarizer is used to polarize normally.
incident light either along the direction of the Si channels (transverse electric, TE) or orthogonal to them (transverse magnetic, TM). The dimensions of the structure are \( w = 270 \text{ nm}, h = 200 \text{ nm} \) and \( t = 40 \text{ nm} \). \( p \) ranges from 820 to 880 nm. The fabrication process of the structure is illustrated in figure 1(c). First, the electron-beam (EB) resist (ZEPS20A, Zeon Corporation, Tokyo, Japan) was coated on the Si substrate by spin coating. Subsequently, the coated EB resist was patterned through EB lithography (F7000S-VD02, Advantest, Tokyo, Japan). Following this, a reactive ion etching (RIE) system (Plasmalab 80 Plus, Oxford Instruments, Abingdon-on-Thames, UK) was used to etch the Si substrate. A 2-nm thick Ti layer was deposited before the Au deposition using EB evaporation (Peva-400E, Advanced System Technology Co., Tokyo, Japan). The function of the Ti layer is to increase the adhesion between the Si substrate and the Au layer. Lastly, the EB resist and the top Au layer were removed by lift-off in a dimethylacetamide ultrasonic bath at 60 °C. The scanning electron microscope (SEM) images of the fabricated sample are shown in figure 1(d), displaying the top-view and magnified tilt image of the structure.

2.2. Optical and electrical measurements
The reflectance spectra of the fabricated samples were characterized by the FT-IR spectrometer (VIR-300, JASCO, Tokyo, Japan). The center of the structure was illuminated at normal incidence by a C-band wavelength tunable laser source (TLG-210, Alnair Labs Corporation, Tokyo, Japan). The effective area of the structure under illumination was 0.785 mm². A photodiode amplifier (PDA200C, Thorlabs, New Jersey, US) was used to supply a bias voltage on the structure. For each wavelength, the photocurrent was measured with a chopper and a lock-in amplifier (LI5640Y, NF Corporation, Yokohama, Japan). The temporal photoresponse of the structure upon periodic illumination was recorded with an oscilloscope and a mechanical shutter.

2.3. Simulation
The simulated spectra of the absorptance, reflectance and transmittance were computed with the rigorous coupled-wave analysis (RCWA, DiffractMOD, Ruosh Design Group, Ossining, NY, USA). The distributions of electric field, electric potential and current density were computed with the Finite Element Method (COMSOL Multiphysics, COMSOL, Inc., Burlington, VT, USA). The perfectly matched layer (PML) boundary conditions were applied in the z-direction at the top and bottom of the simulation domain, and the periodic boundary condition was applied in the x-direction.

3. Results and discussion
To investigate the optical behavior of the Si channel-separated Au grating structure, the reflectance \((R_{\text{sam}})\), transmittance \((T_{\text{sam}})\) and absorptance \((A_{\text{sam}})\) spectra of the structure for TM-polarized light is first simulated, as shown in figure 2(a). The period of the structure \((p)\) is 840 nm. The absorptance peak (point B) reaches 0.8 at the resonant wavelength of 1524 nm. The measured reflectance \((R_{\text{exp}})\) spectrum, characterized using a FT-IR spectrometer, has a full-width at half maximum (FWHM) as narrow as 24 nm. The measured and simulated reflectance spectra are not perfectly matched due to imperfections in the fabrication, including the undesired deposition of a thin Au layer (about 2 nm in thickness) on the sidewalls of Si channels during the EB evaporation, and the formation of rounded corners at the bottom of the Si channels during the Si etching. The simulated electric field distributions in the x- \((E_x)\) and z-direction \((E_z)\) at the points A \((\lambda = 1300 \text{ nm})\) and B \((\lambda = 1524 \text{ nm})\), which are defined in figure 2(a), are provided in figure 2(b). At a non-resonant wavelength (point A), the electric field of \(E_z\) and \(E_x\) are both quite weak. In contrast, the electric field at the resonant wavelength (point B) exhibits strong enhancement at the corners of the Au slabs and the bottom of the Au/Si interface as a result of the excitation of a surface plasmon polariton (SPP) mode at the Au/Si interface. The measured reflectance variation with the period \((p)\) of the structure is given in figure 2(c). The reflectance dip redshifts when the period increases from 820 to 880 nm, demonstrating the facile tunability of the resonant wavelength. This is further demonstrated in figure 2(d), which shows the simulated reflectance variation with light wavelength and period of the structure. The resonant wavelength of the SPP mode redshifts linearly with the period, matching well with the measured reflectance variation. Figure 2(e) shows the measured reflectance spectra at different incident angles of light. Only one reflectance dip occurs at the resonant wavelength at normal incidence \((0°)\), while the reflectance dip splits when the incident angle increases to \(3°\) and \(6°\). Moreover, the distance between the two dips increases with the incident angle. This splitting of the resonance is due to the strong angular dependence of the SPP mode, which is indicated in figure 2(f) where the simulated reflectance variation with light wavelength and incident angle of light is shown. The reflectance splits when the incident angle increases from \(3°\) to \(25°\), and the SPP mode becomes weaker when the angle is even larger.

To evaluate the photocurrent response of the structure, the responsivity \((R)\) is calculated by \(R = (i_{\text{ph}} - i_d)/P_{\text{in}}\) where \(i_{\text{ph}}\) represents the photocurrent, \(i_d\) represents the dark current and \(P_{\text{in}}\) represents the effective power of light illuminated on the structure. The applied bias voltage is kept at 1.0 V. The measured responsivity for the structure

\[ R = \frac{(i_{\text{ph}} - i_d)}{P_{\text{in}}} \]
with a period of 850 nm and the corresponding reflectance spectrum are given in figure 3(a). The incident light is TM polarized with an incident power of 10 mW. The responsivity exhibits the spectral selectivity in the C-band. The peak responsivity reaches 72.5 nA mW$^{-1}$ at the resonant wavelength of 1538 nm, suggesting that the responsivity variation in the C-band is a result of hot electrons that are excited by SPPs coupled at the resonant wavelength. The responsivity variation is opposite to the variation of the reflectance over the C-band. The reason for this is that the absorptance and reflectance of the structure have opposite behaviors in the C-band, as indicated in figure 2(a), and the number of generated hot electrons is directly proportional to the absorption. The measured responsivity for the structure with a period of 840 nm and the corresponding reflectance spectrum are shown in figure 3(b). Through changing the period of the structure, the resonant wavelength is shifted to 1520 nm. The responsivity steadily decreases across the C-band as the wavelength increases, dropping from 64.5 nA mW$^{-1}$ ($R_1$) at 1530 nm to 19.0 nA mW$^{-1}$ ($R_2$) at 1565 nm. The responsivity variation within the C-band ($R_1$-$R_2$)/$R_1$·100% reaches as high as 70.5%, demonstrating the excellent spectral selectivity in the C-band. Because of the limited range of the tunable laser, the responsivity at wavelengths below 1530 nm is not measured. The responsivity and reflectance also show the same inverse behavior in the C-band.
To investigate the polarization dependence of the structure’s responsivity, the photocurrents at different polarization angles are measured, as shown in figure 3(c). The incident power of light is 10 mW. 0° is defined as the electric field direction pointing along the direction of the Si channels. The two insets illustrate the electric field ($E$) and magnetic field ($H$) orientations for TM and TE polarizations. The dependence of photocurrent on the polarization angle demonstrates that the Si channel-separated Au grating structure is strongly polarization-dependent. The generation of hot electrons is enhanced and a large photocurrent is observed for TM polarization (90°, 270°), whereas fewer hot electrons are generated for TE polarization (0°, 180°, 360°). To further study the polarization effect, the normalized electric field distributions in one periodic unit of the structure at TE and TM polarizations are simulated, as shown in figure 3(d). The period of the structure is 850 nm, and the light wavelength is 1538 nm. (e) The measured photocurrent variation with the incident power of the TM-polarized light at the wavelengths of 1530, 1538 and 1546 nm. The period of the structure is 850 nm. (f) The temporal photoresponse of the structure upon the periodic illumination. The light is TM polarized with a power of 10 mW, the light wavelength is 1538 nm, and the period of the structure is 850 nm.
polarization, the electric field is strongly enhanced at the corners of the Au slabs and the bottom Au/Si interface, indicating the presence of SPPs at the interface. From this comparison, we can conclude that the SPPs can be excited with TM polarized light and this facilitates the generation of hot electrons in the structure, whereas they cannot be excited with TE polarized light. Figure 3(c) shows the photocurrent variation with the incident power of light at the wavelengths of 1530, 1538 and 1546 nm. The light is TM-polarized and the period of the structure is 850 nm. The photocurrent shows a linear dependence on the incident power of light, confirming the generation of hot electrons results from the single photon-hot electron interaction [11]. Since the resonant wavelength is 1538 nm, the measured photocurrent at this wavelength is much larger than any other wavelength. The temporal photoresponse of the structure upon the periodic illumination (controlled by a mechanical shutter) is shown in figure 3(f). The light is TM-polarized with an incident power of 10 mW and the wavelength is 1538 nm. The calculated rise time ($\tau_\text{r}$) and falling time ($\tau_\text{f}$) upon periodic illumination are 150 and 166 ms, respectively.

To obtain a better understanding of the behavior of hot electrons and the process governing the photocurrent, a band diagram illustrating the generation and transport processes of hot electrons in the Si channel-separated Au grating structure is shown in figure 4(a). The Fermi level of the positive (+) Au slab is $E_F$ and the Fermi level of the negative (−) Au slab is $E_F + qV_a$ upon the application of a bias voltage $V_a$ on the Au slabs. Since the energy (hν) of the C-band light is higher than the Au/Si barrier height (\(\varphi_b = 0.75\ eV\)) [34] and lower than the bandgap of Si (\(E_g = 1.12\ eV\)), electron-hole pairs cannot be directly generated in the Si from light absorption. Therefore, only hot electrons generated in the Au grating contribute to the photocurrent. Hot electrons with an energy exceeding the barrier height can go across the Au/Si Schottky barrier into the conduction band of the Si. Since hot electrons are simultaneously generated in the negatively and positively biased Au slabs, they can generate the forward ($I_{\text{Forward}}$) and backward photocurrents ($I_{\text{Backward}}$) that flow in the opposite directions. These two opposite photocurrents produce a net photocurrent $I_{\text{ph}} = |I_{\text{Forward}} - I_{\text{Backward}}|$ that depends on the properties of the metal, the barrier height and the bias voltage [15]. In order to examine the spatial distributions of energy and hot electrons in the structure, we simulate the distributions of normalized absorbed power and hot electron generation rate in one periodic unit of the structure, as shown in figure 4(b). The hot electron generation rate $G$ is calculated by [16]

$$G = \frac{\varepsilon_i |\vec{E}(\vec{r}, \omega)|^2}{2\hbar},$$

where $\varepsilon_i$ is the imaginary part of the permittivity of Au, $\omega$ is the angular frequency of incident light, $\vec{E}(\vec{r}, \omega)$ is the electrical field density at the position $\vec{r}$, and $\hbar$ is the reduced Planck constant. It is seen that the Au slabs absorb almost all the power of the incident light. From the distribution of the normalized hot electron generation rate in figure 4(b), it is observed that the energy and hot electron generation rates are strongly enhanced at the Au corners and bottom Au/Si Schottky barrier, indicating the presence of SPPs at the interface.
rate, it is found that most of hot electrons are generated in the vicinity of the Au/Si interface, which ensures the generated hot electrons have a low thermalization loss and high transport efficiency.

To further investigate the electrical properties of the structure, the electric potential distribution in the structure is simulated, as shown in figure 4(c). The period number is simplified to 5 and the bias voltage $V_a$ is applied on the leftmost and rightmost Au slabs in the simulation. The electric potential in the structure drops from $V_a$ at the positive slab (leftmost side) to 0 V at the grounded slab (rightmost side). As such, the electric field directions represented with the arrows are unified to point from the horizontal-left to the horizontal-right. The arrow indicates the direction of the electric field and the arrow length represents its intensity. The current density distribution and the current flow direction in the structure are further simulated, as shown in figure 4(d). The enlarged partial view shows one periodic unit of the structure. The arrows indicate the direction of current flow and the arrow length represents its intensity. Seen from the simulation, the current density is concentrated in the Au slabs. Since the electric field directions are unified to point from the horizontal-left to the horizontal-right in the structure, the current formed by hot electrons transport flows horizontally in the structure.

4. Conclusions

In summary, we proposed a Si channel-separated Au grating structure for spectrally selective photodetection in the C-band. The structure efficiently guides and confines incident light at the corners of the Au slabs and the Au/Si interface through exciting SPPs. By taking advantages of the SP-induced hot electrons, the structure overcomes the native limitations from the bandgap of semiconductors and achieves sub-bandgap photodetection with relative high responsivity. The measured responsivity for the structure with a period of 850 nm shows the spectral selectivity in the C-band. The peak responsivity reaches 72.5 nA mW$^{-1}$ at the resonant wavelength of 1538 nm, suggesting that the responsivity variation in the C-band is a result of hot electrons that are excited by SPPs coupled at the resonant wavelength. The measured responsivity for the structure with a period of 840 nm steadily decreases across the C-band as the wavelength increases. The responsivity variation within the C-band reaches as high as 70.5%, demonstrating the excellent spectral selectivity in the C-band. With these outstanding properties, the proposed structure is promising for numerous applications that require narrowband and spectrally selective detection.

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Data availability statement

Any data that support the findings of this study are included within the article.

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