

論文の内容の要旨

論文題目 Plasmonic channel structure for sensing and photodetection at
telecommunication wavelengths

(プラズモニクチャネル構造によるセンシング・通信波長での光検出)

氏 名 肖 紅彬

肖紅彬

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 these outstanding properties, plasmonic nanostructures have been widely used to enhance the performance of optoelectronic devices, such as photocatalysis devices, solar energy harvesting devices, lasing devices, and photodetectors. 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. Photodetectors incorporating hot electrons are also referred to as hot electron photodetectors. 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, including antennas, nanorods, nanowires, waveguides, metal gratings, and gratings with the deep trench cavities. Among them, the grating-based structures offer an efficient approach to realize strong light confinements by generating surface plasmon polaritons (SPPs), which results in a resonant photocurrent response with narrow bandwidth. However, most reported Si-based NIR photodetectors have low responsivity and broad

bandwidths with responsivities that change slowly with the target wavelength, limiting their practicality as spectrally selective photodetectors.

In this thesis, a Si channel-separated parallel grating structure that exhibits the spectrally selective photodetection in the C-band (1530–1565 nm) is first investigated. The structure efficiently guides and confines incident light at the corners of the Au slabs and the Au/Si interface through exciting the SPP mode. The electric field is strongly enhanced at the Au/Si interface due to the presence of SPP mode, which ensures the generated hot electrons have a low thermalization loss and high transport efficiency across the Au/Si barrier. By taking advantages of the plasmon induced hot electrons, the structure overcomes the native limitations from the bandgap of semiconductors and achieves sub-bandgap photodetection with relative high responsivity and large variation in the C-band. The measured responsivity for the structure with a period of 850 nm shows the spectral selectivity in the C-band and the peak responsivity reaches 72.5 nA/mW at the resonant wavelength of 1538 nm and bias voltage of 1.0 V. The measured responsivity for the structure with a period of 840 nm steadily decreases across the C-band as the wavelength increases. The responsivity drops from 64.5 nA/mW at 1530 nm to 19.0 nA/mW at 1565 nm, representing a variation of 70.5% over the C-band. The measured dark current is smaller than 10 nA at the bias voltage of 1 V. 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. Since the proposed structure shows a strong field enhancement at the metal/dielectric interface due to the channel-coupled surface plasmon resonance (SPR) mode, and the coupling of hollow cavity mode and SPR mode, the structure is very sensitive to the minute variation of the refractive index of the surrounding medium and this enables it to be a label-free biochemical sensor. The electric field is strongly enhanced around the Si channels for the channel-coupled SPR mode at normal incidence. For the coupling of hollow cavity mode and SPR mode, the electric field is strongly enhanced in the hollow cavity between the adjacent Si channels and on the top-surface of the Si channel at the tilted incidence. The measured sensitivity of the structure reaches a value as high as 967 nm/refractive index unit (RIU) with the figure of merit (FOM) approaching 60, which are higher than most reported refractive index sensors with plasmonic nanostructures. Additionally, the resonant wavelength of the structure is demonstrated to be readily tuned through changing the Si channel width, so that a wider resonant wavelength range can be included for practical applications.

To further increase the responsivity of the Si channel-separated parallel grating structure, the Au grating is reshaped from the traditionally parallel structure to an

interdigitated structure that are separated by U-shaped Si channels. For distinguish purpose, the interdigitated structure is named after Si channel-separated interdigitated grating structure. Since the cross sections of the two structures are the same, the absorptance and electric field distribution in the two structures are also the same. The absorptance spectrum of the structure shows a sharp peak with a modulation of 0.81 at the resonant wavelength and the full width at half-maximum (FWHM) is as small as 23 nm. The photocurrent response of the structure reveals a remarkable improvement. The measured responsivity reaches 804 nA/mW at the resonant wavelength of 1550 nm and the bias voltage of 0.08 V, which is 11 times of that of the Si channel-separated Au grating structure and shows a competitive performance with respect to previously reported Si-based NIR photodetectors. The measured dark current is as small as 0.01 pA at 0 V and it is still less than 10 nA even the bias voltage increases to 0.08 V, which enables the structure to be an eligible NIR photodetector. Apart from this, a theoretical model is also conducted to evaluate the photocurrent response under light irradiation regarding the optical and electrical properties of the structure. According to the model, the theoretical calculation for the structure reproduces the spectral dependence of responsivity and exhibits the same spectral selectivity with the experiment in the C-band.

We also propose a distributed Bragg reflector (DBR)-film structure and a DBR-based grating structure in this thesis. The DBR-film structure achieves a high absorptance (0.83) at the resonant wavelength (1547 nm). The generation of hot electrons is enhanced by the excitation of Tamm plasmons (TPs) at the metal/DBR interface, facilitating the photocurrent response. The DBR-based grating structure further increases the absorptance and shows a larger modulation compared with the DBR-film structure and Si-based Au grating structure. The electric field in this structure is strongly enhanced at the last SiO₂/Si interface, indicating the coupling of Fabry-Perot (FP) resonance and TP resonance. Due to the strong field enhancement at the Au/Si interface, the generation of hot electrons is further facilitated and a large photocurrent is produced. The structure also exhibits a narrowband and high-responsivity in the NIR, which opens a new way for the TPs based hot electron photodetectors.