論文の内容の要旨

NIR Spectrometer by a Schottky Photodetector with an Au Grating
(金回折格子を有するショットキー型光検出器による近赤外分光器)

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1. Introduction

Near infrared (NIR) spectroscopy quantitatively or qualitatively analyzes materials by the light spectrum. It is widely used in many fields such as agriculture, medicine, and so on. Diffraction gratings combined with photodetector array are widely used in spectrometers. The gratings diffract the incident light into different angles depending wavelength. Each wavelength then passes through an optical path and is detected at different position in photodetector array. Therefore, the longer the optical path is, the wider the different wavelengths is separated. The higher spectral resolution is thus obtained. However, when the scale of the spectrometers become smaller such as micro-spectrometers, the tradeoff between the optical path and the resolution has to be made. As a result, grating based micro-spectrometers have low resolution. In this thesis, to overcome this optical path issue in the diffraction grating based spectrometers. Surface plasmon resonance (SPR) instead of the diffraction of a grating was used to wavelength-selectively couple the light. It was combined with a Schottky photodetector. The optical path is no longer necessary. The light coupling by SPR has high SNR. Therefore, using SPR is able to achieve a high spectral resolution. Previous works have proved that photodetectors enhanced by SPR have the wavelength-selectivity. One of the researches proved that a Schottky photodetector enhanced by SPR of gratings is wavelength-selective at angle of incidence where SPR occurs, which is the same characteristic used in this thesis. However, in their work, a continuous spectrum was not measured. A convex lens and 4 pairs of detectors were used to measure the photocurrent varying the wavelength of the incident light. The photocurrent of each pairs contains the response of a range of wavelengths. In this thesis, a matrix calculation method is proposed to separate the response of each wavelength. The spectrums of light with single wavelength and mixed multiple wavelengths were obtained.

2. Theory

The structure of the proposed photodetector is shown in **Fig. 1 (a)**. An Au grating was fabricated on an n-type silicon substrate. The grating is used to wavelength-selectively couple light into surface plasmon polaritons (SPPs) by SPR. The Au and the n-type silicon form Schottky junction which collects the hot electrons into a photocurrent. SPPs propagate along the interface of a metal and dielectric with the electromagnetic mode in the dielectric side and the oscillating electrons mode in the metal. The SPR coupling condition of a metal grating is that the wave vector of the light along the surface matches that of SPPs. For different wavelengths, the SPR occurs at a unique angle, SPR dip angle. At the angle, the corresponding wavelength is intensively coupled to SPPs and produces a photocurrent, while other wavelengths are reflected by the grating. Therefore, the photodetector is wavelength-selective at SPR dip angle. The detecting wavelength range is discretized to wavelength components. A responsivity matrix $\boldsymbol{R}$ is constructed. It is formed by responsivities of each wavelength component at each SPR dip angle. It describes the wavelength-selectivity at SPR dip angle of the detector. Responsivity as a characteristic parameter of a photodetector is the efficiency of power of light to photocurrent. Using the matrix, the power of each wavelength, the spectrum, can be calculated from the photocurrent at SPR angles by the equation $\boldsymbol{P}=\boldsymbol{R}^{-1}\boldsymbol{I}$. The diagonal entries of the responsivity matrix are selected to be the responsivities with SPR enhanced. Therefore, the matrix is invertible and the above equation is workable. To illustrate the property of the responsivity matrix, photocurrent curves of three wavelength of a photodetector and its responsivity matrix are shown in **Fig. 1 (b)**.

3. Simulation and Fabrication

The profile parameters of the Au grating affect the responsivity and the spectral resolution of the photodetector. Therefore, Au gratings with different slit height, the thickness of Au layer, the pitch and the fill factor are simulated using COMSOL Multiphysics. The electric field distribution with and without SPR is shown in **Fig. 2 (a)**. Reflectance curves of different wavelength calculated from the simulation are shown in **Fig. 2 (b)**. The curves prove that SPR dip angle of each wavelength is different. Au grating with pitch of 3.2μm, fill factor of 0.5 and Au layer thickness of 100nm varying the slit height from 60nm to 220nm were simulated. The results are shown in **Fig. 3**. The incident wavelength is 1500nm. As the slit height increasing, the reflectance at SPR dip angle reduces while the FWHM increase. Because a small FWHM is preferred for high spectral resolution, the slit height of 80nm to 100nm is appropriate for the simulate grating. Au gratings varying thickness of the Au layer from 100nm to 10nm were also simulated. The slit height was set to be 100nm, the other parameters remained the same as the simulation of the slit height. As shown in **Fig. 4**, the SPR dips are almost the same when the thickness is larger than 60nm. However, as it further decreases, the SPR dip becomes blunt. It is because the electric field begin to pass through the Au layer and the coupling of the light into SPPs on the surface decreases. A thick Au layer is preferred. Thickness larger than 40nm is appropriate for the simulated grating. The results of Au grating varying pitch from 2μm to 4μm and fill factor from 0.2 to 0.8 are shown in **Fig.5** and **Fig. 6** respectively. The pitch mainly affects the value of the SPR dip angle and excitation diffraction order, while the fill factor relates to the reflectance and FWHM. A pitch making the two adjacent SPR dip angles far away each other should be selected to provide a large detectable wavelength range. For the simulated grating, fill factor 0.5 is better. The Schottky barrier height was calculated from a measured IV curve of a fabricated Schottky photodiode. The calculated barrier height was 0.78eV, which is lower enough to detect the NIR light. The photodetector was fabricated by lift-off process. A photoresist grating firstly was fabricated on top of an n-type silicon wafer. Then Au film was deposited on top of the wafer. The photoresist then was removed by stripper solution and an Au grating with isolate slit was produced. Another Au layer was deposited again to form the same structure as the simulation. An aluminum film was deposited on bottom of the wafer as electrode of the detector.

4. Experiments and Results

A photodetector was used to confirm that the Au grating is able to couple the light by SPR and produce a photocurrent by SPPs. The reflectance and photocurrent versus angle of incidence were measured. The experimental set up and results are shown in **Fig. 7** and **Fig. 8**. In order to obtain spectrum, the responsivity matrix of a photodetector was constructed. The parameters of the grating were measured by SEM and shown in **Fig. 9**. Photocurrent curves of light from 1470nm to 1570nm with interval of 5nm were measured. The experiment set up and results are shown in **Fig. 10 and Fig.11**. The SPR dip angle of each wavelength is different. The photocurrent of the wavelength with SPR enhancement is larger than those of the other wavelengths at a SPR dip angle. The responsivity matrix was obtained by diving the photocurrent at SPR dip angles of each wavelength by the measured incident power of the wavelength. The diagonal entries of the matrix were responsivities with SPR enhanced, which were larger than the entries of the same row or column. The matrix thus is invertible and is able to use to calculate the spectrum. The property of the inverse matrix of the responsivity matrix was investigated by analyzing each row vector. The waveform of each row has a ‘W’ shape peak to increase the multiplication factor of the SPR enhanced photocurrent to separate the response of each wavelength. Finally, a whitelase source was used to provide the testing light with single wavelength and mixed multiple wavelengths. Two commercial spectrometers with spectral resolution of 12nm and 5nm FWHM were used to detect the spectrums for comparison. Some of the measured spectrums by the three methods of single wavelength and mixed multiple wavelengths are shown in **Fig. 12**. The photocurrent curves of light with multiple wavelengths are also shown in **Fig. 12**. They can presented the peak position of the wavelength components. However, they cannot provide the precise shape of spectrum, because the response of all the wavelengths is mixed together. This proves the matrix calculation method is necessary and workable to separate the response. The peak wavelength position measured by the photodetector is within 5nm different with those by the two spectrometers. The difference on FWHM of each wavelength peak were approximately within 10nm. Therefore, with the proposed matrix calculation method, the photodetector can achieve a comparable spectral resolution as the two spectrometers. In the experiment, the photodetector was able to separate wavelength difference of 20nm. The calculated theoretical spectral resolution of the photodetector is 13nm.

5. Conclusion

In conclusion, we fabricated a Schottky photodetector with an Au grating and proposed a matrix calculation method to realize the spectrum measurement in NIR range of 1470nm to 1570nm. There is no optical path needed to separate the wavelength, which cause low spectral resolution in conventional grating based micro-spectrometer. The spectral resolution of the photodetector depends on the FWHM of the SPR dip, which is relatively small and can be improved by designing the profile parameters of the grating. Therefore, the work in this thesis provide an option for achieving high-resolution and small-scale spectrometer without the limitation by optical path.