Study on angle-resolved sensitivity of SOI photodiode with surface plasmon antenna

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学 位 論 文 要 旨

Abstract of Doctoral Thesis

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論文題目：表面プラズモンアンテナ付きフォトダイオードにおける角度分解受光感度の研究
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Abstract：

Recently, there has been a trend in the imaging technology to capture the plenoptic information. This is enabled by a so-called plenoptic camera or light field camera, which detects the direction of the incident light as well as its intensity, in contrast to the traditional camera which forms images only by the intensity information. Such kind of advanced camera realizes interesting applications such as three-dimensional (3D) image reconstruction, depth-of-focus extension, lensless imaging, etc. The plenoptic cameras were previously built in the form of the camera array, moving optical component, mirror array, mask-based image sensors, microlens array in front of an image sensor. The existing cameras suffer from large size, complexity in fabrication, long-term stability, high cost, etc. The conventional techniques also have issues in the trade-off between the angular and spatial resolution. To increase the angular resolution, substantial amount pixels need to be employed at the expense of the spatial resolution. Due to these drawbacks, the need for developing angle sensitive pixels (ASPs) emerges.

It has been proposed to make ASP compatible with cost-effective standard complementary metal-oxide-semiconductor (CMOS) fabrication process without the need for process customization, miniaturization of its size makes the camera portable with less cost, it could be arrayed in a plane to detect the incident angle without relying on microlens and could be combined with techniques developed for conventional imaging, it suffers less from the tradeoff between the spatial and angular resolutions and makes the data processing simple by directly capturing the direction of light by each pixel. The conventional ASPs based on Talbot pixels with two diffraction gratings stacked over the photodiode successfully realized the angle sensing for application such as range finding, a polarization filter stacked with quadrature pixel cluster (QPC) to reduce the count of sub-pixels were developed, an angle sensing detector consists of a pair of Si nanowire enabled angle detection with a minimum resolution of 0.32º. However, these existing ASPs suffer from the reduced light sensitivity. The quantum efficiency of Talbot pixel is low in general and could not be increased above 45% even after the structural modification which

requires the process customization. Thus, CMOS compatibility, ease of fabrication, high angle resolution, and high quantum efficiency need to be considered in the development of ASP.

The objective of this thesis is firstly to propose a pixel level CMOS photodetector with angle sensing capability and should offer high quantum efficiency. Secondly, mathematical equations to predict the azimuth-elevation peak incident angle of our device is formulated by considering the physical mechanism of angle detection. Then, the predicted peaks in the form of spatial pattern for azimuth-elevation angular representation are plotted for data analysis. Next, the optimized photodiode is designed based on electromagnetic simulation of 3D finite-difference time-domain (FDTD) method, and absorption efficiency in the same form is evaluated to represent the peaks as spatial pattern. Then, an automated experimental setup to measure the photocurrent of our detector in azimuth-elevation angle is constructed and the spatial pattern is plotted to represent the directivity of our proposed pixel. Finally, effects of the grating type and the grating period, and dependence of polarization angle and the potential of the SOI PD with SP antenna as an ASP are discussed.

We propose the ASP based on silicon-on-insulator (SOI) photodiode (PD) stacked with surface plasmon (SP) antenna of one-dimensional (1D) line and space grating and two-dimensional (2D) hole array grating. When an SP antenna is integrated over the photodiode, sensitivity enhancement occurs. The enhancement has selectivity of wavelength, incident angle and polarization. When the phase matching condition is satisfied, the diffracted light from the antenna couples efficiently with the propagating mode of the SOI layer. The azimuth-elevation incident angle (θ, ϕ) sensitivity of the proposed device is evaluated in this study. Based on the phase matching condition, theoretical prediction for the azimuth and elevation angular detection in pixel level is explained. Experimentally, the SP antenna is patterned over the SOI PD by electron beam lithography. The azimuth-elevation angle dependence of the quantum efficiency of the fabricated device is measured to verify the theoretical and FDTD predictions. Understanding in the incident-angle-dependent characteristics of the proposed PD among theory, simulation and experiment is attained. Due to the ease in fabrication, the compatibility with CMOS integrated circuit technology, the ability to sense both parameters of incident angle, i.e. azimuth and elevation angles, and the high quantum efficiency, present results may open up a new field of ASPs integrated in a image sensor for applications such as 3D image reconstruction, depth-of-focus extension and lensless imaging.