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Abstract—The quantitative optical measurement of deep sub-wavelength features with sub-nanometer sensitivity addresses the measurement challenge in the semiconductor fabrication process. Optical scatterings from the sidewalls of patterned devices reveal abundant structural and material information. We demonstrated a parametric indirect microscopic imaging (PIMI) technique that enables recovery of the profile of wavelength-scale objects with deep sub-wavelength resolution, based on measuring and filtering the variations of far-field scattering intensities when the illumination was modulated. The finite-difference time-domain (FDTD) numerical simulation was performed, and the experimental results were compared with atomic force microscopic (AFM) images to verify the resolution improvement achieved with PIMI. This work may provide a new approach to exploring the detailed structure and material properties of sidewalls and edges in semiconductor-patterned devices with enhanced contrast and resolution, compared with using the conventional optical microscopy, while retaining its advantage of a wide field of view and relatively low cost.

Index Terms—Light scattering, nanoscale microscopy, polarization, semiconductor.

1. Introduction

In recent years, gallium nitride (GaN)-based semiconductor nanowire devices have attracted considerable...
attention owing to their attractive optoelectronic properties and wide potential applications in nanophotonics\textsuperscript{[1]-[5]}. The sidewalls of the patterned devices, typically coated with metal, play a significant role in the performance of these devices\textsuperscript{[6]}. Resolving sub-100-nm characteristics of sidewall scatterings, especially the thicknesses of the layers and particles on the sidewalls’ surfaces, in the etched pattern is one of the most important issues in the fabrication of semiconductor-patterned devices. Conventional inspection tools, such as the atomic force microscopy (AFM) and scanning electron microscopy (SEM), have high resolving power for the nanoscale inspection. However, they cannot fulfill the rigid requirements of online inspections, especially the high demand for the measurement speed over large volumes. Optical microscopes that are cost-effective and have a large imaging area and high resolving power are highly required to examine the structural and material properties of these patterned devices\textsuperscript{[7]-[10]}. Recently, some researchers have reported the fabrication of GaN-based devices with nanoscale patterned structures on silicon substrates, placing an even higher demand on the resolution of optical inspection tools\textsuperscript{[11],[12]}. Due to the optical diffraction limit, the achievable resolution of a conventional optical microscope is intrinsically limited to ~200 nm in the visible light spectrum. Thus, the development of new modalities of optical microscopes, to achieve higher resolution in the scattering fields of semiconductor and metallic devices, especially in patterned devices, is an active area of research\textsuperscript{[13]-[15]}. Moving towards breaking the diffraction limit, researchers have demonstrated optical imaging of the sidewall layers in patterned devices based on structural and scattering information\textsuperscript{[16]}. Recently, a scatterometry technique was developed, which is capable of measuring nano-textured samples with nanometric accuracy over a field of view on the order of cm\textsuperscript{[17]}. The dark-field illumination has also been reported as a better option for obtaining scattering information of sidewalls compared with the bright-field illumination\textsuperscript{[18]-[20]}. Recently, we demonstrated the utilization of a parametric indirect microscopic imaging (PIMI) system for light scattering measurement of Cu$_2$O particles\textsuperscript{[21]}, and others have proven the capability of this technique for sensing the scattering signals from a sub-micrometer particle\textsuperscript{[22]}. As reported previously, the PIMI technique achieves high resolution of nanoscale anisotropic structures by measuring and filtering the far-field optical scattering variation upon precise modulation of the illumination polarization\textsuperscript{[22]}. This measurement scheme primarily takes advantage of the high sensitivity of the polarization status of scattered photons from anisotropic structured materials, especially when the sample exhibits abrupt dimensional and dielectric variations at the locations of photons that have been scattered. Such scheme of PIMI is exactly suitable for the case when inspecting the scattered optical fields from the sidewalls of semiconductor-patterned devices, where the dielectric constant abruptly changes from the top layer to the substrate layer at the sharp sidewall edges. In a previously reported proof-of-concept study, we demonstrated the suitability of the PIMI technique for imaging surface particles and line edges of semiconductor devices as well as the contrast and resolution enhancements achieved with PIMI\textsuperscript{[23],[24]}. In this paper, we investigated the PIMI measurement technique further by numerically modelling the photon scattering and imaging processes, and numerically solving Maxwell’s equations for anisotropic and periodic patterned device structures\textsuperscript{[25]-[31]}. The finite-difference time-domain (FDTD) simulation and AFM results were used to validate the capability of PIMI to resolving the sub-wavelength features of the sidewalls in semiconductor-patterned devices. In fact, in addition to the previously reported image contrast enhancement\textsuperscript{[23]}, fine sub-wavelength rippled sidewall features were clearly resolved by PIMI in various semiconductor-patterned devices. These new findings by PIMI may suggest opportunities to explore detailed structural and material properties of the sidewalls and edges in semiconductor-patterned devices, with enhanced contrast and resolution compared with using the conventional optical microscopy, while retaining the advantages of a wide field of view and relatively low cost.
2. Configuration of the PIMI System and Sample Preparation

As shown in Fig. 1, the PIMI system uses an Olympus reflection microscopic system (BX51), presented in Fig. 1 (a), as the basic optical patch, and a polarization-modulation module with the angle precision of 0.05° is inserted in the illumination beam path. In the beam path between the objective and the imaging sensor, a quarter-wave plate (QWP) and a high-extinction-ratio polarizer are inserted, with the fast axes oriented at 45° and 90°, respectively, with respect to the paper plane. The imaging sensor is a charged couple device (CCD) manufactured by Basler (piA2400-17gm) with the 3.45-µm pixel resolution and an output dynamic range of 12 bits. The 3.45-µm pixel resolution results in the maximum potential resolving power of 34.5 nm, if the diffraction limit is broken, and the Nyquist principle is fulfilled in the microscopic system when working with a 100× objective[24]. Using the control and analysis software (ANISOSCOPE) developed by our group, the polarization angle of the illumination was modulated precisely from 0° to 360° with the step of 18°, and the far-field scatterings under each illumination condition were automatically recorded. The intensity variations of each pixel in the recorded images were then fitted with the theoretical prediction, as presented in Fig. 2. Pixels with intensity variations that could not be fitted to the theoretical prediction with a certain fitting merit index, e.g., correction determination factor (Adj-R-square) > 0.95, were filtered out from the resulting images. Then, the filtered images were utilized to calculate the Stokes parameters[24]. The measurement was performed with the dark-field illumination for two different semiconductor-patterned devices with the periodic structure shown as Figs. 1 (b) and (c).

![Fig. 1. Construction of the PIMI system: (a) scheme of the polarization PIMI system measurement; (b) three dimensional and (c) top view showing the periodic structure of a patterned device.](image)

The sample was fabricated using the buffered oxide etch method. The fabrication process involves six steps: 1) A 500-nm thin SiNₓ film was deposited on a GaN wafer followed by 2) photoresist coating, 3) light exposure, 4) photoresist development, 5) dry and removal of SiN/SiO₂ (mask), and 6) hydrogen annealing[11]. The width of one finger and the gap between two fingers are 80 µm and 100 µm, respectively. The thickness of each finger is 500 nm. The sample was first cleaned by an ultrasonic bath with deionized water and then air-dried for half an hour before the experiment.
The difference between the conventional microscopy and PIMI is illustrated in Fig. 3. In the conventional optical microscopy, the shape of the far-field point spread function (PSF) is traditional, as presented in Fig. 3 (a), and its resolution is limited by the diffraction limit. However, in PIMI, due to the difference in the scattering information obtained with different linear polarizations, the PSF shape deviations from the one obtained by the conventional microscopy are shown in Fig. 3 (c). The near-to-far-field coupling-based quantification of the far-field PSF and filtration of the irrelevant noise produced from the neighboring points enable the PIMI system to resolve the structural features of the sample under measurement (SUM) beyond the diffraction limit. The conventional microscopic and PIMI dark-field images recorded with the same optics are presented in Figs. 3 (b) and (d), respectively. The PIMI parameter $\phi$, which denotes the angle between the slow axis and the $E_x$ axis, resolves the structural and scattering information of the sidewall more effectively than the conventional microscopic image ($I_0$). Various sub-wavelength scattering details from the edge of the sidewall were revealed in the $\phi$ image, which is barely seen in the conventional microscopic image ($I_0$). The intensity profiles along the white lines in Figs. 3 (b) and (d) were plotted for further comparison as shown in Fig. 4. As expected, the intensity profile shape obtained with the conventional microscopy exhibited just one peak, whereas within the area under the peak of the $I_0$ profile, several peaks appeared in the intensity profile of the $\phi$ parameter image. This suggests the capability of PIMI to sense sidewall structural information beyond the diffraction limit.

**Fig. 2.** Measured data and fitted curve of the intensity variation of one pixel from same position under different polarization angles.

**Fig. 3.** Comparison of conventional imaging and PIMI systems: (a) illustration diagram of a conventional imaging system on the anisotropic SUM, (b) conventional dark-field image with a 100× magnification, (c) dark-field modulated polarization parameter imaging system, and (d) PIMI dark-field image with a 100× magnification.
The details of the PIMI measurement principle and its applications for imaging sub-wavelength nanoparticles were previously reported\[24,32\]. However, its utilization for the characterization of line-shaped edges was not thoroughly investigated or validated. This is due to the difficulty faced in solving Maxwell’s equations for the far-field scattering optical field under relatively complex boundary conditions in the current study. Therefore, we adopted the FDTD method to numerically solve Maxwell’s equations under PIMI measurement illumination conditions, e.g., rotating the polarization of the illumination, to obtain the scattering distributions in the far field, represented by the parametric images used in PIMI. As presented in Fig. 5, far-field indirect parametric images of the depolarization (\(I_{dp}\)), the sine of the phase difference between \(E_x\) and \(E_y\) (\(\sin \delta\)), and \(\phi\) were calculated at different locations, including the straight and curved edges of the patterned device, described in Fig. 1.

3. Results and Discussion

As explained in Section 2, PIMI is capable of obtaining optical images (mappings) of Stokes parameters with high resolution by measuring and analyzing the far-field optical scattering intensities of the sidewalls of patterned devices\[24\]. These images of indirect parameters of scattered optical waves can be further exploited to obtain structural and compositional information of these sidewalls with nanoscale resolution owing to the high sensitivity of Stokes parameters to sample anisotropy. Throughout this work, images were taken with a dark-field illumination configuration, as it imparts higher sensitivity to optical anisotropy compared with the bright-field illumination\[18\].

Fig. 6 compares the conventional microscopic and PIMI images for the same sidewall of the sample (Fig. 6 (a)). In Fig. 6 (c), the indirect image shows a ripple of scattering intensities from the edge of the sidewall, which is not shown in the conventional microscopic image (Fig. 6 (b)). A comparison between the \(I_0\) and \(\phi\) images was performed by plotting the intensity profiles along the lines presented in Figs. 6 (b) and (c) and the results are drawn in Fig. 6 (d). The peaks that appeared in the \(\phi\) image intensity profile, i.e., the red line in Fig. 6 (d), clearly confirm the capability of PIMI to sense sidewall structural information beyond the diffraction limit. Moreover, it demonstrates that the edge spread function of the \(\phi\) image is much narrower than that of the \(I_0\) image, as indicated by the two dotted circles in Fig. 6 (d). Interestingly, two edge spread functions appeared in the intensity profile of the \(\phi\) image, whereas only one edge was revealed in the \(I_0\) image. This result indicates that PIMI owns much higher contrast and resolving power compared with using the conventional microscope.

Furthermore, a comparison between conventional microscopic, PIMI, and AFM imaging was performed by imaging the same area of the sample, as presented in Fig. 7. Also, multiple morphological features were utilized
to locate the same sidewall in the conventional microscopic image \(I_{00}\), PIMI image \(\phi\), and AFM image, as indicated by the rectangles and circles in Fig. 7 (a) to Fig. 7 (c). The zoomed-in images of the rectangular areas, which cover the edge of the sidewall, were taken for detailed analysis and comparison of imaging results obtained from the conventional microscopy and PIMI (Figs. 7 (d) and (g)). By plotting the intensity profile along the white line across the edge of the sidewall, the resolving abilities of the conventional microscopy and PIMI are demonstrated in Figs. 7 (e) and (f). Significant improvement in the resolving ability of the structural features of sidewall scattering is shown in the intensity profile of the PIMI \(\phi\) image in Fig. 7 (f). As the PIMI \(\phi\) image corresponds to the polarization azimuth of the scattered optical field, it is highly influenced by anisotropy of the sidewall when the scattering light with a certain polarization status. This is reasonable, as proven by the comparison between conventional microscopic and PIMI images in Fig. 7. A conventional microscope only records the intensity of scattered photons from the sidewall, but the information imposed on the polarization status variation of the scattered optical fields is annihilated. Conversely, in PIMI, the anisotropic scattering effect of the sidewall on the precisely controlled polarization of the incident optical wave is recorded and further enhanced by following the fitting and filtering procedures, thus resulting in high sensitivity of the PIMI image to the structural sidewall features.

**4. Conclusion and Perspectives**

In summary, an optical approach, namely PIMI, was presented to measure the sub-wavelength features of the sidewalls of semiconductor-patterned devices. PIMI demonstrates high potential for metrology applications in the
A semiconductor-patterned device was investigated using the presented technique, and the sub-wavelength features on the sidewalls were resolved by recording and analyzing the polarization status of the scattered optical field. The PIMI results were compared with those of AFM and the conventional microscopy to verify the superior resolving power of PIMI. The high resolving power on the sidewalls of semiconductor devices using the proposed method opens new opportunities for the development of a high-resolution, low-cost, and easy-to-use optical metrology system for nanoscale structures in integrated semiconductor circuits.

**Disclosures**

The authors declare no conflicts of interest.

**References**


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