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Super resolution optical measurements of nanodefects on Si wafer surface using infrared standing evanescent wave

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ABSTRACT

We propose a novel optical measurement technique that enables the sensitive evaluation of microdefects on a Si semiconductor wafer surface beyond the diffraction limit. The proposed measurement technique is based on a hybrid technique combining a super spatial-resolution measurement method using a structured illumination and a highly sensitive dark-field inspection method using an infrared evanescent illumination. Theoretical and experimental analyses suggest that this technique makes it possible to measure defects with 100-nm spatial resolution nondestructively with a wavelength of 1064 nm without the need for time-consuming processes such as probe scanning.

1. Introduction

With the increasing demand for higher efficiencies in the semiconductor manufacturing industry, in-process quality control based on nanometrology is rapidly gaining importance [1]. In particular, nanodefects measurement on the surface of a Si semiconductor wafer substrate is an important quality control factor for realizing high productivity and reliability of semiconductor device fabrications [2–4]. Various types of optical surface evaluation methods have been proposed because they have several advantages such as nondestructiveness and high-throughput characteristics primarily due to their remote sensing capabilities [4–9]. These methods have also been applied to the Si wafer defects measurements [10–17].

In general, especially for fine evaluations of polished surfaces such as those of Si wafers and optical elements, a light scattering method using total internal reflection (TIR) is well known as an extremely sensitive defect measurement method. In this method, light energy distribution, which is called evanescent light, localizes only the surface, thereby making vastly superior dark-field observations possible [18–21]. This method can be employed for measurements of the surface defects of Si wafers on the basis of highly sensitive dark-field observations under the TIR condition; an infrared laser is required as an illumination beam to obtain transparent properties for Si. Although dark-field observations under the TIR condition allow us to detect surface defects with high sensitivity, infrared light prevents us from characterizing finer optical surface properties due to the low lateral resolutions that are restricted by the diffraction limit depending on the relatively longer wavelengths of the infrared light.

By using near-field scanning optical microscopy (NSOM), we can easily characterize the evanescent field and evaluate the defects with nanoscale resolutions even with the infrared illumination [16]. However, this method has intrinsic disadvantages especially in the in-process measurements because its application is limited to small measurement areas with lower measurement speeds.

In order to overcome the abovementioned problems, we propose the application of a hybrid optical evaluation method comprising a highly sensitive dark-field inspection method, which uses an infrared evanescent illumination, and a super-resolution measurement method, which uses a structured illumination, to the surface defects measurement of Si wafers. One of the primary improvement factors for the lateral spatial resolutions of the proposed method depends on the modulated frequency of the illuminated light. Hence, by taking advantage of the high value of the refractive index of Si, our proposed method can sensitively evaluate microdefects on Si semiconductor wafer surfaces with a spatial lateral resolution less than 100 nm even when infrared laser beams with highly sensitive dark-field observations under TIR conditions are used. In this study, we have verified the feasibility of the proposed method from theoretical, numerical, and experimental viewpoints.

2. Super-resolution defects measurement using infrared standing evanescent wave

Fig. 1 shows a schematic diagram of the new concept of the surface defects measurement method that employs an infrared standing evanescent wave. An infrared standing evanescent wave is formed on a Si wafer surface corresponding to the TIR interface by the superposition of incident light and counter-propagating incident light. The illuminated light distribution is vertically confined within several hundred nanometers from the Si wafer surface because the evanescent light intensity decreases exponentially in the vertical direction [16]. Moreover, the infrared standing evanescent wave has sinusoidal distributions in the lateral

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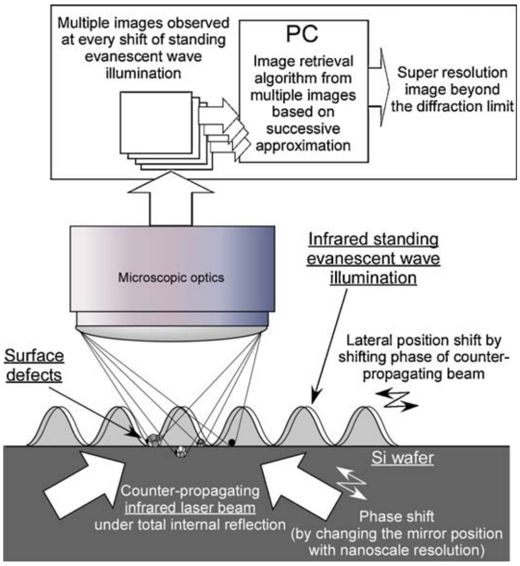

Fig. 1. Concept of surface defects measurement method using infrared standing evanescent wave.

direction, wherein the peak-to-peak distance depends on the wavelength in the TIR medium.

If microdefects such as particulate contamination, micro-scratches, or even internal defects near the surface (subsurface defects) exist on the surface, they cause evanescent wave distribution disturbances, and scattered light is then generated from them. This scattered light distribution from the microdefects can be magnified and detected through far-field imaging optics with high sensitivity as a superior dark-field observation using TIR. Such far-field optical imaging of the scattered light distribution is dominated by the diffraction limit. Because the point spread function of the far-field imaging optics acts as a low-pass filter, the high-frequency information of scattered distributions is lost in the far-field optical image obtained by the imaging optics. By using this method, multiple scattered images can be detected by shifting the standing evanescent light at nanometer scales in the lateral direction. Since the multiple images and the corresponding standing illumination distributions are known, we can expect to reconstruct the scattered distribution with higher frequencies by using successive approximations (Fig. 2) [22]. In this manner, we expect to achieve super spatial resolutions beyond the diffraction limit even under the far-field conditions without the time-consuming process of a probe approaching and scanning, as is the case with near-field optical microscopy.

In this super spatial-resolution method using a standing evanescent wave, improvements in the spatial resolution primarily depend on two factors [22] – a spectrum extension of the far-field optical system by the high-frequency modulation of illumination distribution [23] and an extrapolation effect [24] of the retrieval algorithms of successive approximations. Although it is difficult to analytically define the latter factor due to its sensitivity to noise, the former can be analytically defined using Fourier theory. Further, the lateral resolution caused by the spectrum extension can be expressed using the Rayleigh criterion as follows [22]:

$$Lateral\_resolution = \frac{1.22}{(2\mathrm{N.A.}/\lambda) + (1/T)} = \frac{1.22}{(2\mathrm{N.A.}/\lambda) + ((2n \cdot \sin\theta)/\lambda)} \quad (1)$$

where λ, T, N.A., n, and θ denote the wavelength of the light source, the peak-to-peak distance of the standing evanescent wave distribution, numerical aperture, the refractive index of the TIR medium, and the incident angle of the TIR surface, respectively. This equation indicates that the lateral resolution not only depends on the N.A., but also on the peak-to-peak distance of the standing evanescent wave distribution. Further, even though the wavelength of the infrared light is not extremely short relatively, we can take advantage of the higher value of the refractive index of Si to realize improvements in the lateral resolution.

Fig. 3 shows the relationship between the lateral resolution and N.A. of the imaging optics under the following conditions – λ = 1064 nm, T = 188 nm, n = 3.55, and θ = 53°. This graph indicates that the spatial resolving power of the proposed method by the spectrum extension of the modulated illumination is thrice that of the conventional Rayleigh limit with the uniform illumination. Furthermore, lateral resolutions beyond 200 nm can be achieved even with the far-field optics using an infrared laser with the wavelength of 1064 nm. Moreover, the resolution power of the proposed method remains nearly unaffected by the N.A. of the optical system, while the conventional optical microscopic system is directly affected. This fact indicates the practically useful and unique characteristic that highly magnified images can be obtained even under long-working distance conditions.

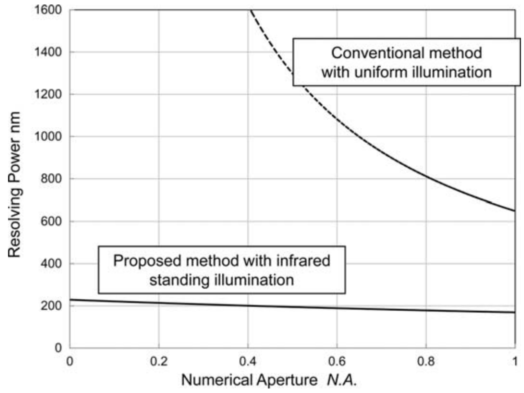

Fig. 3. Relationship between lateral resolution and numerical aperture N.A.

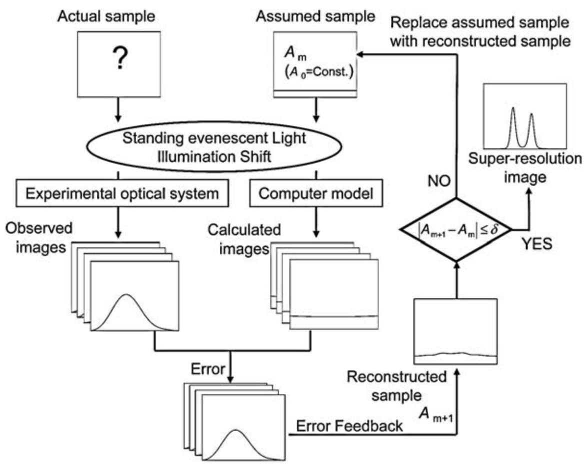

Fig. 2. Scattered distribution retrieval algorithm from multiple observed images with standing evanescent wave.

3. Numerical analysis of lateral resolution improvement

In order to verify the validity of formula (1) and analyze the resolution-improvement characteristics of the proposed method, a numerical simulation based on Fourier optics was performed (Fig. 4). In order to evaluate the resolution power quantitatively, two discrete elements generating scattered light were employed as defect samples, as shown in Fig. 4(A). The two discrete elements were set at a distance of 171 nm, which is identical to the expected resolution power from the nature of the optical spectrum in formula (1) under the following conditions: λ = 1064 nm, T = 188 nm, N.A. = 0.95, n = 3.55, and θ = 53°. Fig. 4(B) is a conventional microscopic image obtained under the same conditions with the normal uniform illumination rather than the standing wave illumination. This image does not allow us to resolve the two scattering elements due to the diffraction limit of

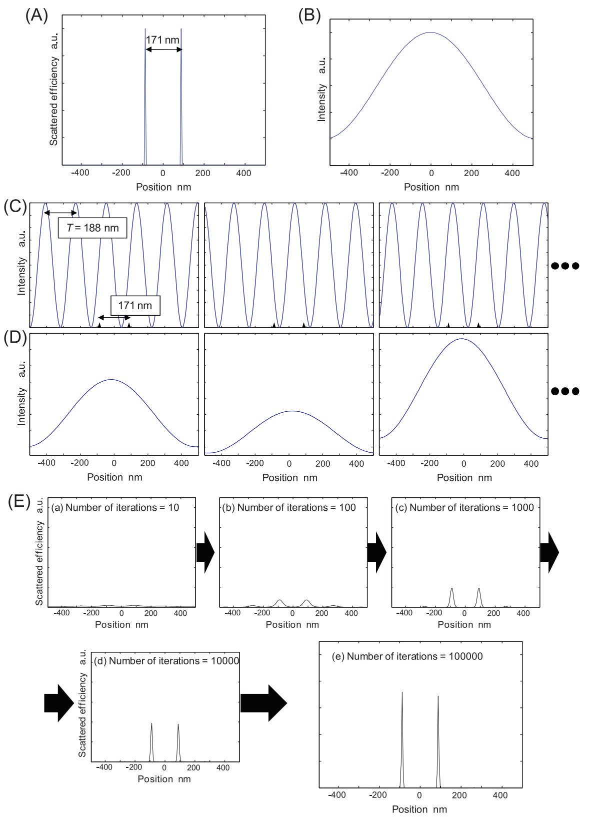

Fig. 4. Numerical simulation results of lateral resolution improvement by the proposed method. (A) Two discrete elements generating scattered light (distance: 171 nm). (B) Conventional microscopic image under the uniform illumination (N.A. = 0.95; Rayleigh limit = 683 nm). (C) Position of the infrared standing evanescent wave illumination relative to two discrete elements. (D) Multiple far-field optical images of each illumination (C). (E) Reconstruction process by the successive approximation.

683 nm. Fig. 4(C) shows the relationship between the position of the two discrete scattered elements and the infrared standing evanescent wave. Fig. 4(D) shows the multiple far-field optical images from the two discrete scattered elements at the position of Fig. 4(C). In this simulation, the infrared standing evanescent wave was shifted 10 times in steps of 17 nm (=T/11). Finally, Fig. 4(E) shows the reconstruction process by the successive approximation whose algorithm was developed by extending the Richardson–Lucy method [25] to a method that can be used to treat multiple images [22]. In this manner, the two discrete scattered elements beyond the diffraction limit can be clearly resolved when the number of iterations is 100,000.

Next, in order to estimate the total resolution power of the proposed method including the extrapolation effects of the successive approximation, we also performed numerical simulations under noise conditions. In actual situations, there are many types of noise factors. As the first analysis step of noise effects, we assume that only the optical images obtained by the imaging optics have random noise, including various noise factors such as errors in the point spread function and fluctuations in the standing evanescent illumination. Fig. 5(a)–(d) shows the super resolution results with distances of 100 nm, 80 nm, 60 nm, and 40 nm,

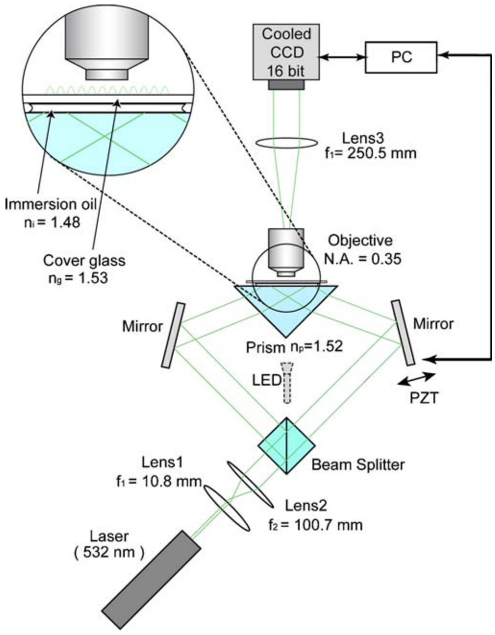

Fig. 6. Experimental apparatus developed for verification of the proposed concept.

respectively; here, the noise levels were set to 10% of the ideal observed image intensity distribution, while the other simulation conditions were identical to those mentioned above. From this analysis, 60-nm separated discrete scattered elements can be resolved with a visibility of 0.48 at noise levels of 10% of the observed image.

4. Fundamental verification experiments for proposed concept

In order to confirm the validity of the proposed concept, we conducted some fundamental experiments. To focus on confirming the fundamental concept, glass substrate was employed as the TIR surface in place of the Si wafer. Fig. 6 shows the experimental apparatus developed for this purpose. This experimental system consists mainly of a continuous wave (CW) green laser (Coherent, Compass 315-150) as a linearly polarized light source with a transparent property for the glass, a trapeziform prism generating TIR conditions on the test surface, a piezoelectric translator for shifting the standing evanescent light with a resolution of 1 nm, an infinity-corrected optical microscope unit with a 16-bit cooled highly sensitive charge-coupled device (CCD) area sensor (Bitran, BD-40), and a PC that controls the CCD and piezoelectric translator and processes multiple images for super resolution imaging.

As the first step, we conducted the basic experiments for resolving a discrete sample of the standard fluorescent particles with a diameter of 200 nm using a relatively lower N.A. objective (0.35). The normal Rayleigh limit under this condition was 927 nm. The other experimental conditions were as follows: λ = 532 nm, T = 325 nm, n = 1.53, θ = 55°, shift times = 7, and shift step = 47 nm. We could clearly resolve a 780-nm separated two-dot sample even when the optics with the Rayleigh limit of 927 nm was used, as shown in Fig. 7. In this manner, the performance of our proposed method using the infrared standing evanescent light with image

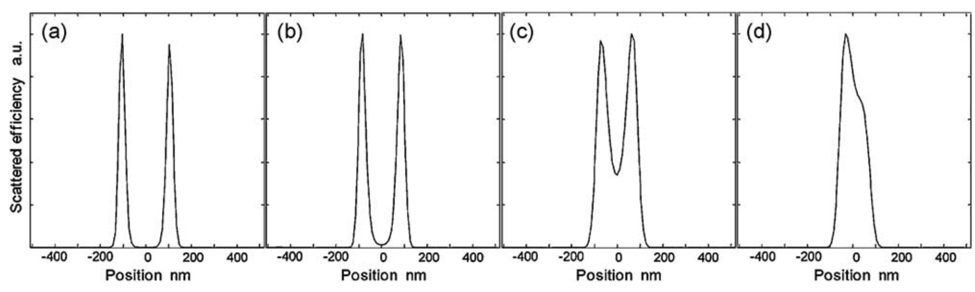

Fig. 5. Super resolution results with the distance of 100 nm (a), 80 nm (b), 60 nm (c), and 40 nm (d) under 10% noise condition.

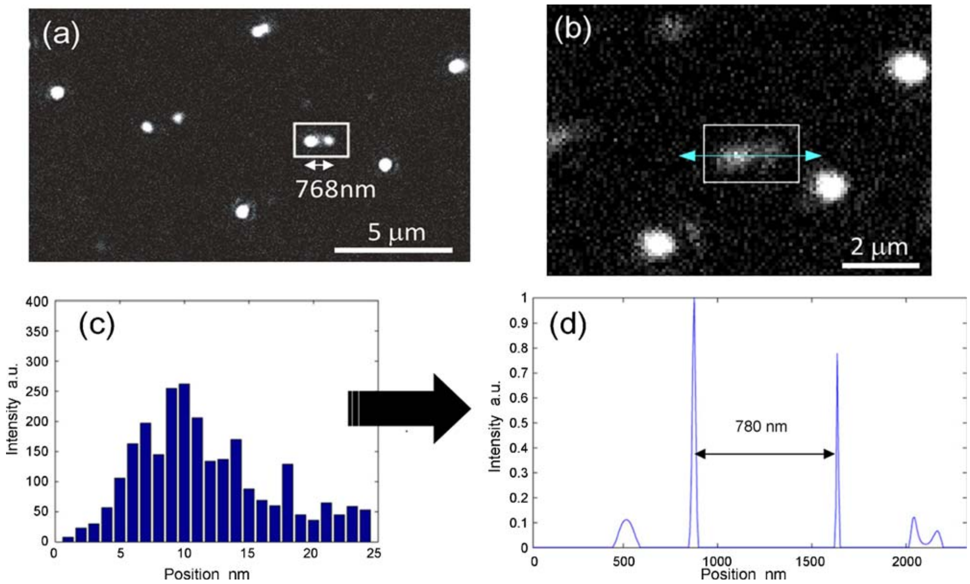

Fig. 7. Experimental results obtained with the developed experimental system. (a) Standard fluorescent sample (observed with N.A. = 0.9; Rayleigh limit: 361 nm). (b) Conventional microscope image (observed with NA = 0.35; Rayleigh limit: 927 nm). (c) Intensity profile of image (b) at the cross-section of the arrow position. (d) Super resolution profile (obtained using N.A. = 0.35; Rayleigh limit: 927 nm).

retrieval has been verified. A detailed experimental analysis of the resolution characteristics due to a difference in coherence is an important future task.

5. Conclusions

We have proposed a novel optical measurement technique that enables the sensitive evaluation of microdefects on a Si semiconductor wafer surface beyond the diffraction limit even under far-field conditions, which implies that time-consuming processes such as a probe approaching and scanning are not needed. The proposed measurement technique is based on a hybrid method combining a super-resolution measurement method using a structured illumination and a highly sensitive dark-field inspection method using an infrared evanescent illumination.

Theoretical analyses based on spectrum extension by the high-frequency modulation of illumination distributions indicate that the proposed method has three-times larger resolving power than the conventional far-field imaging technique by making appropriate use of the higher values of the refractive index of Si. Our numerical analyses suggest that 60-nm separated discrete scattered elements can be resolved with visibility of 0.48 at the noise levels of 10% of the observed image. Further, the fundamental experimental results confirm the proposed concept from the practical viewpoint. These analyses suggest that the proposed method has the potential to evaluate Si wafer surface defects including subsurface defects with a spatial resolution less than 100 nm even with the highly sensitive dark-field detection under TIR conditions using infrared laser beams.

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