Pis'ma v ZhETF, vol.72, iss.9, pp.658 - 661 © 2000 November 10

LASER WRITING OF SUB-WAVELENGTH STRUCTURE ON SILICON (100) SURFACES WITH PARTICLE ENHANCED OPTICAL IRRADIATION

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Submitted 9 October 2000

Spherical 0.5 μm silica particles were placed on Silicon (100) substrate. After laser shinning with a 248 nm KrF excimer laser, hillocks with size of about 100 nm were obtained at the original position of the particles. Mechanism of the formation of the sub-wavelength structure pattern was investigated and found to be the near-field optical resonance effect induced by particles on surface. Theoretical calculation result of the near-field light intensity distribution was presented, which was in agreement with the experimental result. The method of particle enhanced laser irradiation has potential applications in nanolithography.

PACS: 42.82.-m

The field of nanoelectronics has evolved into a major area of investigation. Nanolithographic techniques, such as atom beams [1, 2], electron beams [3], scanning probe tunneling [4 – 6], and scanning near-field optical lithography [7 – 9], are expected to be potential methods in the fabrication of present and future nanodevices. However, due to their incompatibility with the present fabrication processing and their low throughput, the application of these methods is presently confined to experimental stage. Meanwhile, traditional optical lithography is limited to diffraction effect and always relates to complex system and high cost. In this letter, we report a novel, low-cost, and simple optical lithography technique by using particle enhanced laser irradiation.

Standard spherical silica particles (Duke [10]) packaged as low residue aqueous suspensions were used in our experiment. The diameter of the particles is 0.5 μm, with a deviation limited in a range of ±5%. Silicon (100) samples were dipped in 5% hydrofluoric acid for 20 seconds of hydrogen passivation, and rinsed with DI water afterwards. Particles were applied on Si (100) surface and dried by hot air jet. The location of the particles on the substrate before laser irradiation was observed with an optical microscope. As shown in Fig.1a, the particles are spherical and smooth, and many of them are free of aggregation.

A 248 nm KrF excimer laser with pulse duration of 23 ns was used. In order to produce observable laser-induced pattern, beam intensity in the area of the sample was adjusted to about 340 mJ/cm^2. The laser beam was irradiated normally on the Si (100) surface. The pulse number was 200. The sample after laser irradiation was observed again with the optical microscope, as shown in Fig.1b. Comparison of the two pictures, i.e. that before and after irradiation, showed that localized black spots (Fig.1b) appeared at the original position of the particles (Fig.1a). In the two pictures, the original particle

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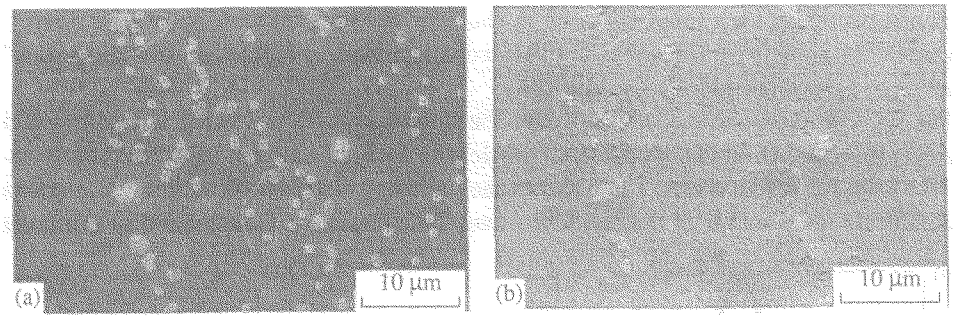

Fig.1. Optical microscope observation of the localized hillocks induced by particle enhanced laser irradiation: surface view before (a) and after (b) irradiation

position (Fig.1a) and the observed corresponding black spots (Fig.1b) were marked with curves.

Field emitting SEM was used to track the black spots that were corresponding to the original particle position. The SEM image Fig.2a shows the black spot observed in Fig.1 is a circular hillock and a curve around the hillock can be seen clearly. This curve around the hillock can also be seen in Fig.2b, the AFM observation. This indicates that the hillocks were produced due to melting of the "hot point". The size of the hillock is about 100 nm with height about 10 nm.

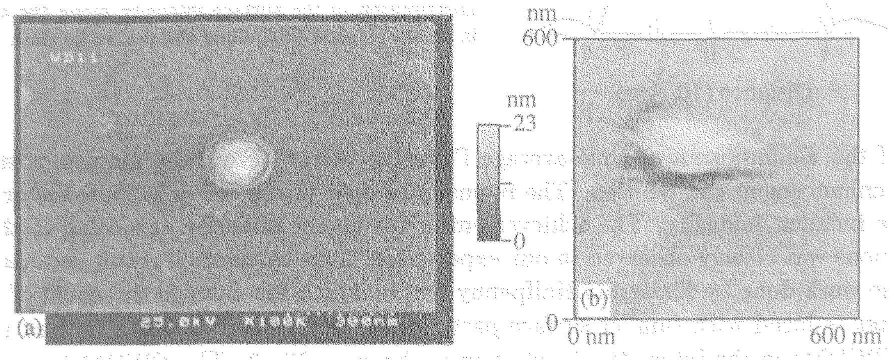

Fig.2. Image of the hillock structrure: (a) SEM and (b) AFM. These pictures presents the different hillocks

The same laser fluence (340 mJ/cm^2) was also applied on clean Si (100) surfaces (without particles), whereas no damage spots were observed. It is obvious that higher intensity was achieved due to the spherical particles in our experiment and this resulted in the formation of the hillocks. The mechanism can be explained as the enhancement of light intensity near the contact area [11 − 13]. Since the characteristic distance between particles and substrate is smaller than radiation wavelength, and particle size is in order of wavelength, particles do not simply play a role of microfocusing lens as in far-field, but relate to the optical resonance effect in near-field. The source of the optical resonance is excitation of partial waves (multipole modes of spherical cavity) [14]. The optical resonance produces high intensity zone in the near-field region and, naturally, when this high intensity zone is on the substrate surface it can lead to formation of "hot points"[2]. These "hot points" produced the hillocks.

The light intensity on the surface under the spherical particle was calculated by solving the electromagnetic boundary problem "particle on surface" [12, 15, 16]. "Mathematica-4" [17] was used for calculations. Fig.3 shows the intensity distribution within the plane perpendicular to wave vector of the incident wave. This intensity, I, is defined as normalized value of the z-component of time-average Poynting vector. From the picture, a strong optical enhancement can be seen. The intensity of light in the center is 20 times greater than the incident intensity. The achievement of the higher intensity according to theory calculations was clearly observed in our experiment. This calculation result can also explain the work done by Kane and Halfpenny [18] in which the damage threshold of glass substrates reduced with smaller surface particle coverage. The full width on half maximum (FWHM) in the intensity distribution is shown in Fig.3. The FWHM is equal to 80 nm, which agrees with the hillock size of 100 nm. This confirmed that sub-wavelength structure was achieved in our experiment.

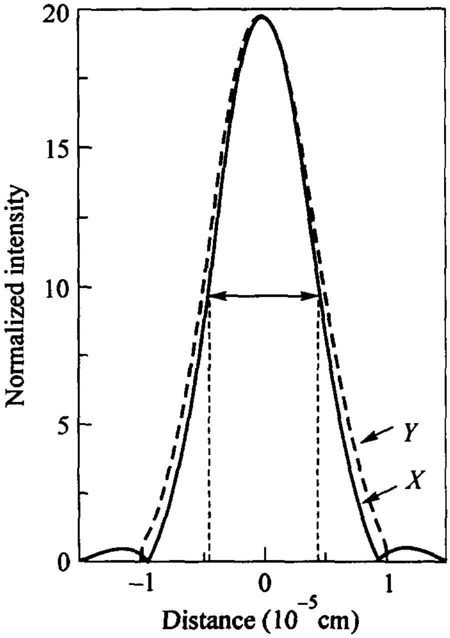

Fig.3. The light intesity distributions (z-component of the averaged Poynting vector) on the substrate surface under the spherical particle (calculations with the Mie theory). Vector **E** of the incident plane wave is directed along the x axes, vector H along the y axes. Distribution of the surface intensity along the x-axes is shown by solid line, along the y-axes by dash line

The small nanoparticles have potentially useful optical, optoelectonic and material properties that might lead to application in nanostructure fabrication [19]. Although 0.5 μm (submicron) spherical particles, discussed at the present paper, work in different mechanism, they too have the same potential in nanofabrication by producing enhanced light intensity in the near field. Further theoretical calculation shows that even higher line resolution below 100 nm can be achieved by selecting suitable particle size and wave-

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[2] It follows from the Mie theory calculations [11 – 13] as well as from more precise calcullations [12], which take into account the secondary scattering of radiation reflected by substrate.

length. We do not discuss here the technical problem, related to particle arrangement and positioning.

In conclusion, we have reported a novel lithographic technique, where particles were applied on a silicon surface and sub-wavelength structure was achieved with particle enhanced laser irradiation. The mechanism was found to be the near-field optical resonance effect induced by particles on surface. Calculation result was presented by solving the electromagnetic boundary problem. Compared to other nanolithographic techniques, the method of particle enhanced laser irradiation needs not a complex system, and uses neither a mask nor a resist, but simply relies-on the near-field optical resonance effect to achieve higher resolution and intensity. It hence may have greater potential in nanofabrication.

Addition: When this paper was ready for publication, we received information from the Konstanz and Madrid groups, that they also found a similar optical field enhancement effect using shorter laser pulses (from 150 fs to 6.5 ns) [20].

The authors would like to thank Dr. S.M.Huang, Ms. W.J.Wang and Mr. X.Y.Chen for their kind assistance in our experiment. The authors also wish to thank Dr. Z.H.Mai (AMD, Singapore) for his contributions to our work. We are thankful to authors of [20] for rapid information about their experiments. B.L. is thankful to Prof. S.Anisimov for discussions and to people in Data Storage Institute at National University of Singapore for their hospitality. B.L. is also thankful to the Russian Basic Research Foundation (grant # 98-02-16104) for financial support.

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