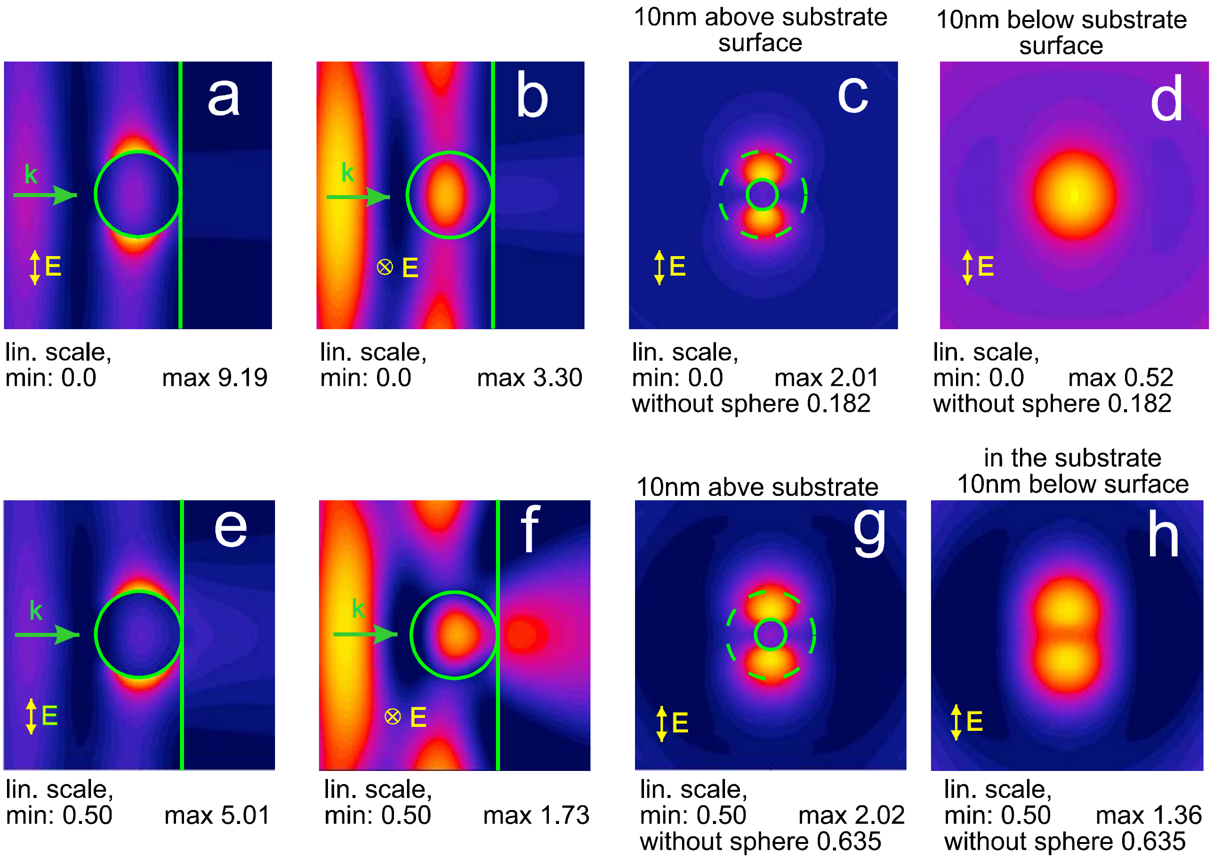
IV Laser-cleaning of Substrate Surfaces

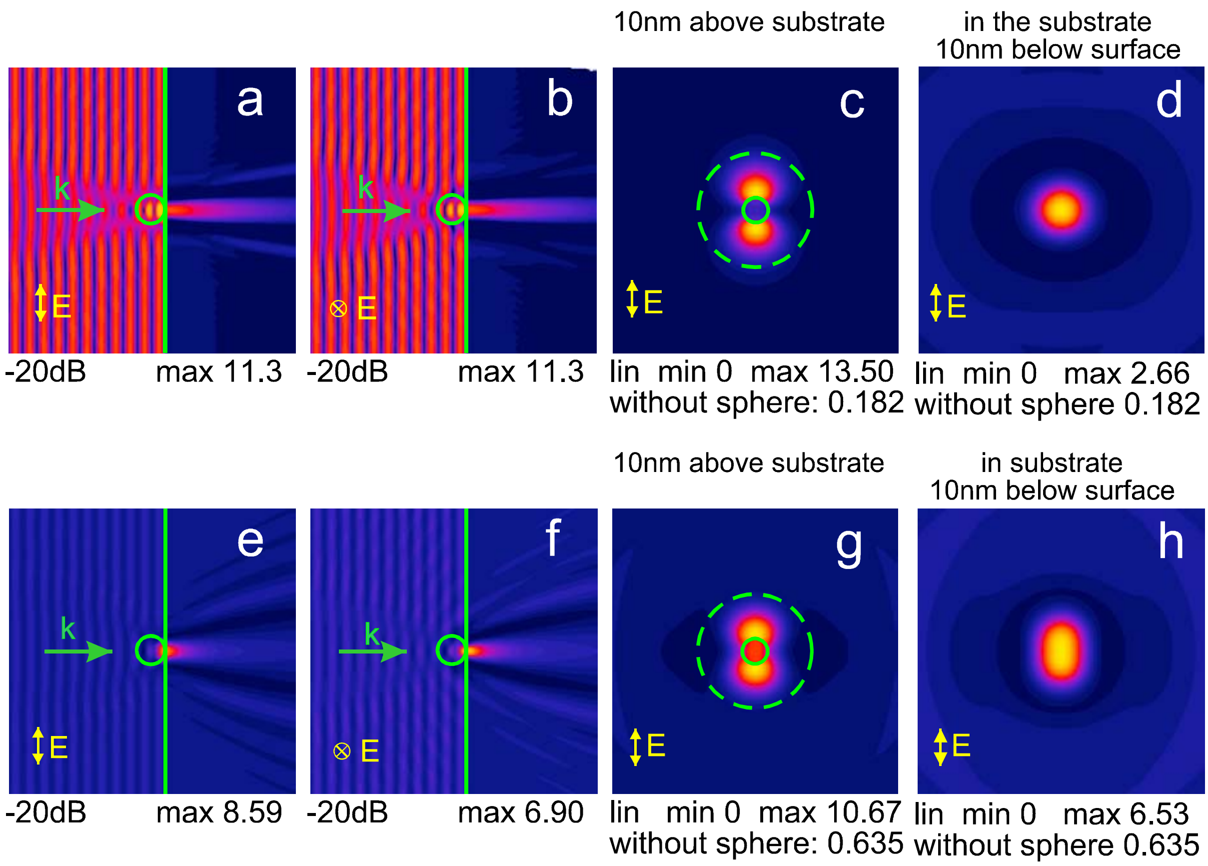
In microelectronics, silicon wafers are normally cleaned by chemical methods, but for the production of devices in the nanometer regime, most of these methods are unsuitable, because many chemical substances cannot be prepared with sufficient purity. In this case, high-power laser beams may be used for the last cleaning step[1,2,3,4]. In this technique dielectric dust particles residing on the silicon substrate are removed from the wafer by explosive evaporation of silicon beneath the particle. The evaporation is the result of the focussing action of the dust particle on a high-power ns or ps laser beam, which is directed onto the particle. The same technique may, of course also be used to remove dust particles from other substrates, e.g. from glass surfaces, which are designed for optical purposes requiring a high degree of smoothness. The interaction with the substrate is governed by the local intensity of the laser, which is proportional to the square of the electric field. In Fig. IV-1 (top row), the fields, calculated by the MMP technique (compare chapter II), are displayed for perpendicular incidence of the laser at a wavelength of λ=800 nm. The impurity in this case is a spherical polystyrene sphere of radius r=160 nm. These results are compared with those obtained for a glass substrate (bottom row of images). The images are plotted in the plane of incidence (a, e) perpendicular to it (b, f) and in cuts parallel to the interface: 10 nm above the interface in air (c, g), and 10 nm below it, in the substrate (d, h), respectively. In image a, the highest intensity appears in the equatorial plane of the spherical particle just outside the sphere and in the direction of polarisation of the incident wave. The intensity enhancement, referred to the incident laser intensity, amounts to a factor of 9.19. Image (b) shows the intensity in the plane perpendicular to the plane of incidence and with a different scaling range. As in part a, an area of enhanced intensity is observed beneath the particle in the silicon substrate. For a glass substrate similar results are obtained for the two cuts. The intensity in the substrate is, of course, higher in this case due to the much smaller refractive index of glass and the lack of any absorption.. In the planes parallel to the vacuum-silicon interface a double peak structure is obtained in the vacuum and a single maximum in the silicon. For a glass substrate, a double peak structure is also obtained in the substrate, which is sharper above the interface than inside the silicon. Such a double-peaked structure has indeed been observed experimentally in the morphology of the



IV-1: (**a-d**) Polystyrene sphere of radius r=160 nm on a silicon substrate. A laser (wavelength 800 nm), approximated by a plane wave, propagates perpendicular to the interface from the left to the right and is scattered by the sphere. The images are plotted in the plane of incidence (**a**), perpendicular to it (**b**), and parallel to the interface 10 nm above it in air (**c**), and 10nm below it in the substrate (**d**), respectively. All scales linear, minima and maxima of E^2 as indicated, units $(V/m)^2$, electric field of incident laser 1 V/m. (**e-h**) Same as (**a-d**), but for the case of a glass substrate All images are 1x1µm in size.

substrate surface after removal of the particle[5]. The two areas of enhanced intensity are aligned in the direction of polarisation. Fig.s (c,g) indicate an enhancement of E^2 by a factor of 11.0 for the silicon substrate and 3.2 for the glass substrate over the value at the same position in the absence of the particle. In the substrate (Fig.s (d,h)) the enhancement factors are 2.9 for silicon and 2.1 for glass. The next figure shows the results for a somewhat larger polystyrene sphere with a radius of r=400 nm.

The polystyrene sphere acts as a lens, i. e., it focuses the incident laser beam onto the silicon substrate. The intensity enhancement in the focus increases with increasing sphere size. As for the smaller polystyrene sphere considered in Fig. IV-1, only a single field intensity maximum is obtained inside the silicon. In the case of glass, a double structure is obtained, which is more diffuse than for the smaller



IV-2: Polystyrene sphere of radius r=400 nm on a silicon (a-d) and a glass (e-h) substrate . The laser (wavelength 800 nm) , approximated by a plane wave, is incident normally to the substrate surfaceas in fig. IV-1 and is scattered by the sphere. The orientation of the images is the same as in fig. IV-1. The size of the images is 8x8 µm (a,b,e,f) and 2x2µm (c,d,g,h), respectively.

polystyrene sphere. The most significant difference between both substrates is the emission into the substrate, which is highly directional for in the case of silicon, due to the high index of refraction. The field enhancement 10 nm above the interface amounts to 74.2 for silicon and 16.8 for glass. In the substrates the enhancement factors are 14.6 for silicon and 10.3 for glass. Again the increased enhancement for the silicon substrate is caused by the high index of refraction, which results in a stronger focussing (compare Fig.s (a,b) and (e,f), respectively.

Fig. IV-3 displays the data obtained for the larger particle, r = 400 nm, on a silicon substrate, and for oblique incidence (ϑ = 60°) of the laser. As for normal incidence, standing waves are obtained in the vacuum. The wavelength of the standing wave increases, of course, with increasing angle of incidence. The intensity enhancement in the focus is smaller than in the case of normal incidence. The cut parallel to and 10 nm above the interface in the

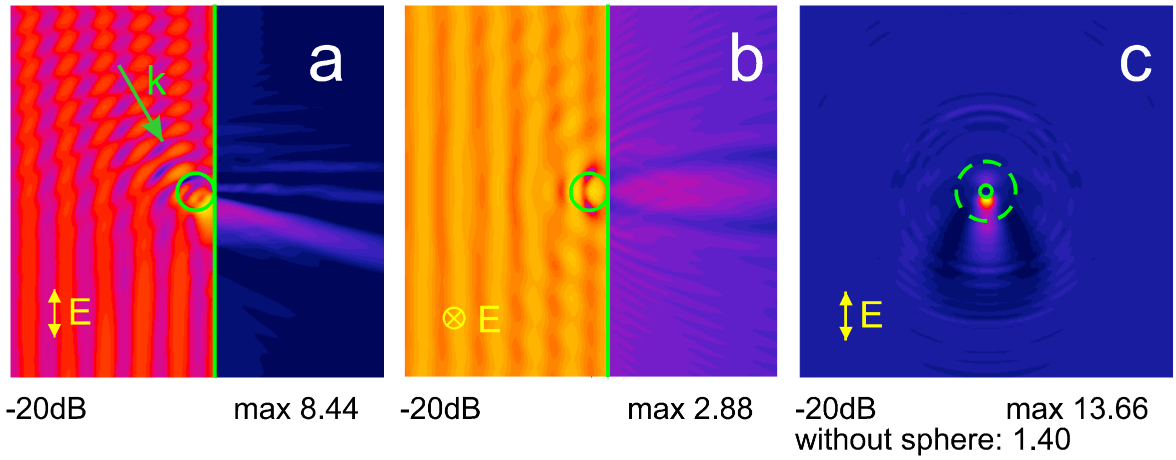


Fig IV-3: Same configuration as in fig. IV-2 (top row), but for the case of oblique (60°) incidence of the laser beam. The size of the images is 8x8 μm (a,b,e,f) and 5x5μm (c,d,g,h), respectively.

vacuum (fig. c) displays only one maximum and not a double structure as in Fig. IV-2.c. As the ablated material will in this case only partly hit the particle, the numerical results demonstrate, that oblique incidence is not promising for laser cleaning of surfaces. The MMP results discussed above will now be compared with experimental results obtained by the Leiderer group[6,7]. Due to the high laser intensity the material of the substrate melts and is partly evaporated. The particle is removed from the surface by the ablated material and submicrometer holes are created in the substrate surface (see Fig. IV-4). These holes are surrounded by walls of resolidified substrate material. Their shapes should reflect the intensity distribution.

The next image shows, that the shape of the holes depends on the polarization of the laser pulses used for the cleaning process. The holes were created with a different laser wavelength (λ=800nm).

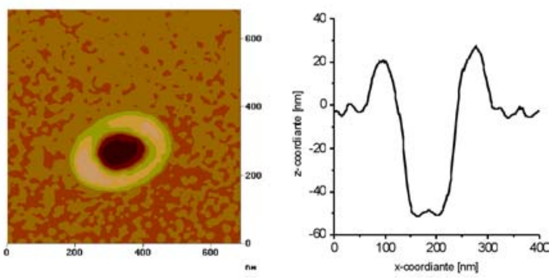


Fig IV-4: left part: AFM-image of a hole created in a silicon substrate beneath a polystyrene sphere (d=800nm) by a femtosecond laser pulse (λ=400 nm, l=150fs) right part: corresponding image profile along the short symmetry axis of the hole. The laser were focussed on a polystyrene sphere with r=800nm deposited on a silicon substrate [7].

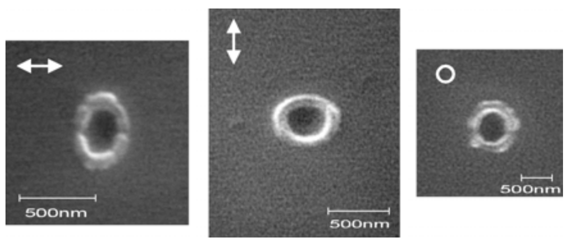


Fig IV-5: SEM images of elliptical holes created in the surface of a silicon substrate by focussing a λ = 800 nm laser on polystyrene spheres of d = 800 nm diameter. The arrows indicate the direction of linear polarisation. The circle in the image on the right indicates circular polarisation.

The hole-shape shown in the middle image of Fig. IV-5 is very similar to the theoretical result shown in Fig. IV-2, part d. The experimental cleaning results obtained with smaller polystyrene spheres are also in good agreement with the theoretical results. Image IV-6 shows the corresponding holes in the substrate material for a polystyrene sphere with r=160 nm and a silicon and a glass substrate, respectively:

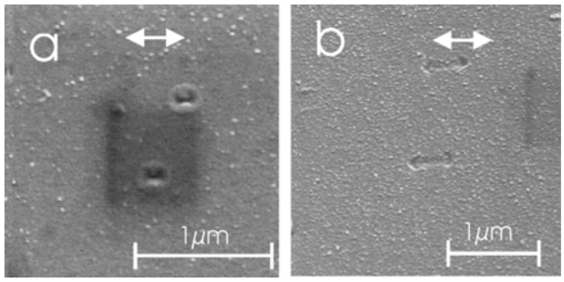


Fig IV-6: SEM images of elliptical holes created in the surface of a silicon substrate (a) and a glass substrate (b), respectively, by focussing a λ = 800 nm laser on polystyrene spheres of d = 320 nm diameter. The arrows indicate the direction of linear polarisation.

The double-peak structures, which can be seen in Fig. IV-6 are similar to the theoretical intensity distribution obtained for a cut 10 nm *above* the substrate surface, in contrast to the case of the larger spheres, where the hole reflects the calculated intensity distribution *below* the surface. The reason for this circumstance is not yet clear, and experiments are under way to clarify this matter. One possibility is, that the much larger intensity enhancement for the larger spheres leads to much deeper holes, and, possibly, if the experiment was carried out at much weaker laser fluences, the double structure would reappear. Another discrepancy between the calculated and experimental results lies in the extremely aspherical holes shown in Fig. IV-6b, obtained with the smaller spheres on a glass substrate. The calculated asphericity, i.e. the ratio of the long axis of the hole to the short one, extinction is larger for a glass substrate than for a silicon substrate (compare Fig. IV-1c,g). The experimental results figure the reverse. The reason for that is also still unclear, but may be related to nonlinear optical effects.

---

[1] V. Dobler, R. Oltra, J. P. Boquillon, M. Mosbacher, J. Boneberg, P. Leiderer, Appl. Phys. A 69 (1999), p. 335
[2] M. Mosbacher, N. Chaoui, J. Siegel, V. Dobler, J. Solis, J. Boneberg, C.N. Afonso, P. Leiderer, Appl. Phys. A 69 (1999), p. 331
[3] P. Leiderer, J. Boneberg, V. Dobler, M. Mosbacher, H.-J. Münzer, T. Fourrier, G., Schrems, D. Bäuerle, J. Siegel, N. Chaoui, J. Solis, C.N. Afonso, Proc. SPIE 4065 (2000), pp. 249-259
[4] M. Mosbacher, H.-J. Münzer, J. Zimmermann, J. Solis, J. Boneberg, P. Leiderer Appl. Phys. A (in print)
[5] M. Mosbacher, H.-J. Münzer, J. Boneberg, P. Leiderer, A. Pack, R. Wannemacher, in preparation
[6] H.-J. Münzer, M. Mosbacher, M. Bertsch, J. Zimmermann, P. Leiderer, J. Boneberg, J. Microsc., accepted for publication
[7] Communication of these results prior to publication by H.-J. Münzer and M. Mosbacher is gratefully acknowledged