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Transient photoinduced diffractive solid immersion lens for infrared microscopy

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We present a scanning near-field infrared microscopy technique using transient solid immersion lenses as near-field probes. The transient SILs were formed by photoinducing a zone plate structure on the surfaces of semiconductor wafers with high indices of refraction. Lenses with different number of zones have been tested using gallium phosphide and silicon wafers and their focusing properties were determined. We demonstrate that transient SILs can have lifetimes longer than 50 ps and provide the same high numerical apertures as conventional SILs. The use of transient SILs eliminates the need for mechanical scanning of the lens or sample, thus providing much faster scanning and the possibility to work with soft and liquid objects. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1519729]

Scanning near-field microscopy and solid immersion microscopy are well-developed methods of optical imaging that provide spatial resolution beyond the optical diffraction limit. Based on the detection of nonpropagating components of electromagnetic field, near-field microscopy does not have a fundamental limit in spatial resolution. Resolution of about $\lambda/20$ has been achieved with aperture probes[1–3] and even higher resolution of up to $\lambda/100$ is available with scattering-type probes.[4–7]

Solid immersion microscopy is an alternative approach to high-resolution imaging, which combines elements of imaging microscopy and probe microscopy. A solid immersion lens (SIL) focuses radiation within a material of a high refractive index, reducing the focal spot diameter by a factor of the refractive index n in comparison with focusing in a vacuum. With the sample positioned on the flat output surface of the SIL, the microscope is operated in the near-field mode using the evanescent field protruding from the SIL into air. SILs can be used as the final elements of either imaging or scanning microscopes. The scanning mode of operation is free from many of the aberrations inherent to the imaging regime and thus provides better spatial resolution. In this mode, a SIL can be considered as a near-field probe with very high throughput.[8–11]

As we have shown previously, photoinduced reflectivity in semiconductors can be used to generate transient IR near-field probes such as small mirrors[12] and apertures.[13] However, these techniques typically require semiconductor substrates no thicker than 1 or 2 μm. These substrates are extremely brittle and difficult to manufacture. In this letter, we demonstrate that a transient diffractive optical element (DOE) can be generated in semiconductors, and particularly a DOE SIL, utilizing the remarkably high refractive indices characteristic of many semiconductors. These elements are much more versatile in comparison with simple aperture probes, and they do not require thin semiconductor substrates. The simplest DOE SIL is a Fresnel lens drawn on one side of a flat semiconductor wafer with its focus on the other side. The fact that such a lens can be created in a transient manner allows for remarkable ease of the scanning procedure by raster scanning the wafer with the sample in the focal plane of the optical system while redrawing the DOE for each wafer position. We will address issues of creating a transient DOE SIL on a semiconductor surface, its lifetime, focusing characteristics, and present the results of near-field imaging with this optical element.

Two materials suitable for creating transient optical elements were tested: GaP ($n=3$) and Si ($n=3.4$). GaP is convenient because its transparency in visible light facilitates sample alignment, while Si provides a higher refractive index, and Si wafers of different thicknesses are readily available. In both materials, free carriers can be generated by the second harmonic of a Ti:Sapphire laser at 400 nm. This wavelength is short enough to provide well-resolved DOE structures for mid-IR wavelengths in semiconductors.

The infrared radiation for this experiment was generated in an optical parametric amplifier (Spitfire, Spectra Physics Inc.) pumped by a Ti:Sapphire laser (1 mJ, 1 ps, 800 nm, 1 kHz). A fraction (30%) of the Ti:Sapphire fundamental was converted to the second harmonic and used as a pump beam to generate the photoinduced electron–hole plasma. To facilitate beam transport, all measurements were performed with the IR light at 6.25 μm, due to the lack of water vapor absorption at this wavelength.

Important parameters for generating the transient DOEs are the transmittance of the pumped material and the lifetime of the diffractive structure. The penetration depths for 400 nm radiation in GaP and Si are 115 nm and 80 nm, respectively,[14] providing high localization of the zone structure in the axial direction. The transmittance of a bulk sample of Si was measured at 6.25 μm as a function of the pump beam fluence, and is presented in Fig. 1. It demonstrates that greater than ten-fold signal attenuation—due to the cumulative effects of reflection and absorption—can be achieved at pump levels several times below the damage threshold.

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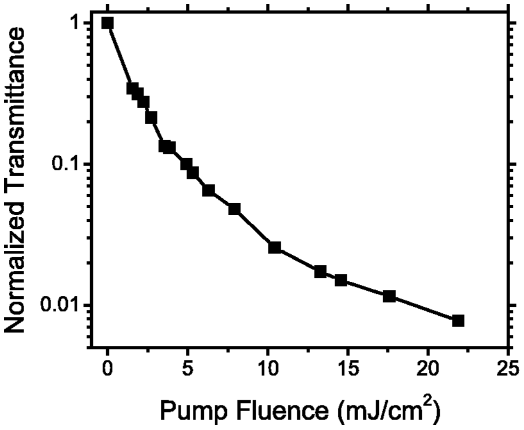

FIG. 1. Transmittance of photoexcited Si at 6.25 μm as a function of pump fluence at 400 nm.

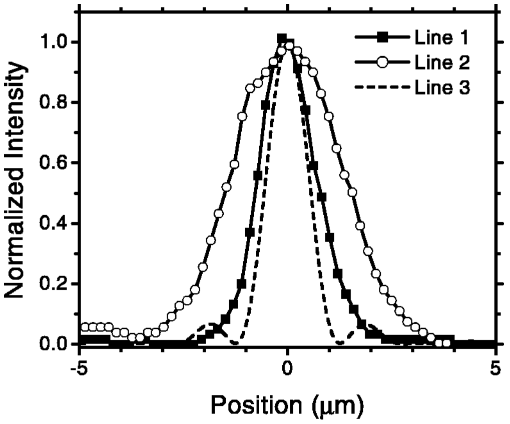

FIG. 3. The intensity cross sections of the images of a 1.8 μm hole imaged with the Si DOE SIL (line 1), GaP DOE SIL (line 2), and with the theoretical intensity distribution of the Si DOE SIL (line 3).

To create the transient DOE SIL, a demagnified image of a lithographic mask with blocked and opened zones was projected onto the surface of the semiconductor with the second harmonic of the Ti:Sapphire laser. The image was formed by a Nikon 50× long working distance microscope objective with 70-fold demagnification. Illuminated regions of the semiconductor became opaque to the IR light and thus worked as ‘‘dark’’ zones, while shadowed areas remained transparent and worked as ‘‘opened’’ zones. Elements of the projection system and IR optics are presented in Fig. 2.

The two semiconductor wafers used in our experiment were 300 μm thick GaP and 28 μm thick Si. Fresnel lenses were designed for both to have a numerical aperture (NA) of about 2.1. Lens diameters of 450 and 60 μm—corresponding to 70 and 15 zones—were required to achieve such a NA on GaP and Si, respectively. The Fresnel lenses were illuminated with a nearly parallel 600 μm diameter IR beam directed normally to the wafer by a small mirror.

IR light scattered from the sample positioned on the output surface of the SIL was collected with a Cassegrain reflecting objective (Ealing, 25×, NA=0.4) and detected with a liquid-nitrogen-cooled mercury–cadmium–telluride detector (KMPV-50, Kolmar Technologies). The field of view of the detecting system was about 10 μm for 6.25 μm IR light. The limited field of view helped to minimize the background signal, almost inevitably present in DOE focusing systems due to their higher-order foci. Constructing the Fresnel lenses with the central zone opaque, to block the zero diffraction order, further reduced the background.

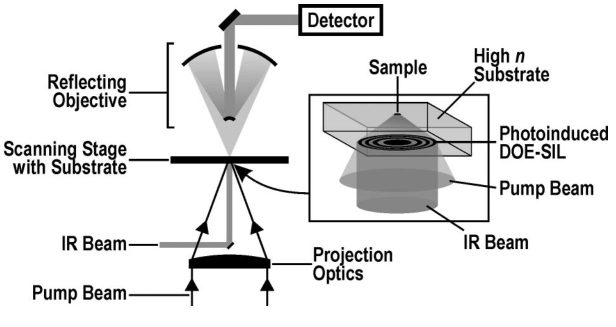

FIG. 2. Experimental setup schematically showing the projection of a mask with the pump beam onto the lower surface of a semiconductor slab using a conventional inverted microscope. The infrared light focused by a transient SIL inside the semiconductor is collected after propagation through the sample located on the upper surface of the slab.

As a test object, we used a 200 nm thick gold coating with small holes on the output surface of the DOE SIL. Figure 3 shows the intensity cross sections taken from the images of a single 1.8 μm hole obtained with the Si DOE SIL (line 1) and GaP DOE SIL (line 2), along with the calculated focal spot profile of the Si DOE SIL (line 3). Both experimental lines represent a convolution of the actual intensity distribution in the focal plane with the hole size. Since the hole size is not larger than the expected focal spot size and the convolution algorithm for a near-field interaction is strongly nonlinear, we assume that the experimental lines are close to the actual spot profile.

The two tested DOE SILs with comparable NAs should have provided similar results; however, they did not. One can see that in our case, the 15-zone lens on Si performs better than 70-zone one on GaP. This is expected because elements with larger diameters are more sensitive to any irregularities in the structure periodicity resulting from the imperfections of the projection system, and—more importantly in our case—they introduce longer delays between IR light traveling from the central and outer zones. This delay is comparable to the IR pulse duration and hinders constructive interference of light scattered from different zones. Furthermore, the spectral bandwidth of the DOE SIL becomes narrower with increasing number of zones, giving rise to chromatic aberrations.

Since the thinner lens showed superior focusing properties in comparison with the thicker one, the 28 μm thick Si based lens was chosen for further study. To demonstrate the ability to resolve more complex objects, an image of two touching 1.8 μm holes was taken. Figure 4 presents the cross section of this image, with the two holes easily discernable by the distinct peaks.

The lifetime of the photoinduced DOE is determined by the recombination and diffusion of the free carriers leading to loss of contrast in the zone structure with time. To evaluate the DOE SIL lens lifetime, we measured its throughput and resolving power as a function of delay between the pump pulse and the infrared pulse. A small hole in a metal coating was again used as a probe to measure the intensity of the focused light and the spot size. Figure 5 shows the dependency of the focused light intensity on the delay between

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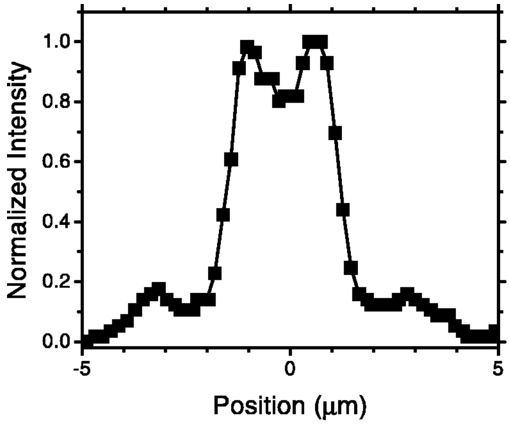

FIG. 4. The intensity cross section of an image of two 1.8 μm diameter touching holes obtained with the Si DOE SIL.

the pump and IR pulses. Although the intensity of the focused IR beam declines nearly exponentially with a 50 ps time constant, the focal spot size varied only by ~30% throughout the range of delays in which the intensity dropped by more than order of magnitude. This indicates that the periodicity of the structure is preserved for a relatively long time while its contrast degrades much faster.

The focusing characteristics and contrast of the transient DOE SIL can be further improved by using advanced diffractive structures. Among them are structures with gradually modulated absorbance, structures utilizing foci of different orders, and, perhaps most importantly, structures employing phase modulation. Phase modulation, which requires the modification of the refractive index over significant depth, can be achieved in semiconductors using pump radiation with a long penetration depth. Such techniques might be used to create three-dimensional structures with possible applications ranging from the focusing of light to creating complex photonic crystals used for signal processing.

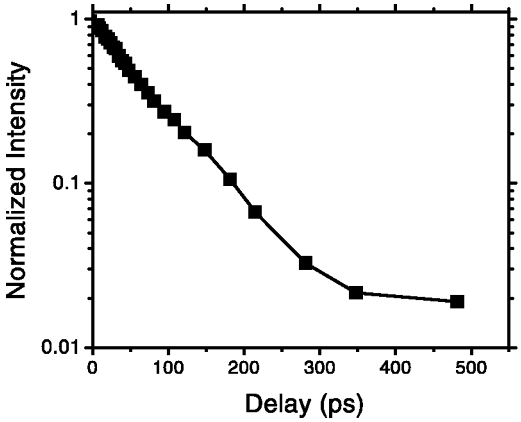

FIG. 5. Intensity of IR light focused by a Si DOE SIL and transmitted through a 1.8 μm hole as a function of the delay between the visible pump pulse and the IR pulse.

In summary, we have demonstrated focusing with a transient SIL created from a photoinduced diffractive optical element on GaP and Si substrates. Such a lens provides similar resolution to conventional SILs, but eliminates the need for the mechanical scanning of the lens or sample. We have also demonstrated that the resolving ability is closely matched to previous transient aperture-based techniques, while using thicker, much more convenient, and readily available substrates.

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