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Near-field infrared microscopy with a transient photoinduced aperture

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We report a method of near-field infrared microscopy with a transient optically induced probe. Photoinduced reflectivity in semiconductors is used to generate a relatively large transient mirror with a small aperture (infrared probe) in its center. Properties of this probe have been studied and first images obtained using the technique are presented. Resolution better than λ/5 at 6.25 μm is demonstrated. Among the advantages of this technique are high optical throughput of the probe, ease in simultaneous visible imaging, and a high scanning rate limited primarily by the pulse repetition rate of the laser system. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1395524]

Near-field microscopy provides optical imaging with resolution far beyond the diffraction limit. By its nature, this technique is a scanning probe microscopy, and a great variety of probes and optical configurations have been developed.[1–3]

Typically scanning is performed along the sample–air (or sample–liquid) interface with atomic force detection feedback to control the probe–sample separation.[4,5] This makes the scanning procedure three-dimensional (3D) and relatively slow. However, many samples (e.g., biological and semiconductor structures) can be prepared on a substrate with a flat sample–substrate interface. In this geometry scanning with a near-field probe can be substituted by modulating the optical properties of the substrate on a subwavelength scale. Ideally, a thin substrate layer should be nontransparent for radiation, providing the possibility of making a small reversible window at any point on its surface.

One physical effect that can be used for this is photoinduced reflectivity in semiconductors.[6] This effect works very well for the mid-IR spectral range ($\lambda > 5\ \mu$m), which is of great interest for many applications. Since the wavelength of mid-IR radiation is about 10 times longer than that of visible light, short pulse visible light lasers can be used to create a transient optical probe with dimensions well below the diffraction limit for mid-IR. In initial experiments on near-field microscopy with a photoinduced probe, a small transient photoinduced mirror (TM) was used as a near-field probe.[7] However, strong background signals caused by light scattered from the sample hindered possible applications of that technique.

In this letter we propose a different type of photoinduced probe, the transient aperture (TA). To generate the TA a broad beam of visible laser illuminates a large area of the semiconductor film except for a small region in the middle that is shadowed (see Fig. 1). This illumination results in creating a large TM with a small transparent aperture that acts as a near-field probe. The large TM in this configuration effectively protects the sample from the IR irradiation, reducing the amount of scattered light and improving the signal to background ratio. We studied the optical properties of the TM and TA experimentally and performed initial experiments on near-field imaging with the TA.

The general scheme of the experimental setup is shown in Fig. 2. Pulsed IR radiation was generated by an optical parametric amplifier (OPA) (Spitfire, Spectra Physics Inc.) pumped by a Ti:sapphire (Ti:S) laser system (1 mJ, 1 ps, 800 nm, 1 kHz). The OPA generated picosecond pulses of IR radiation are tunable from 4 to 10 μm at an energy level of up to 2 μJ. The second harmonic of the residual Ti:S laser radiation was used to pump a photoinduced mirror.

All measurements were performed with IR radiation at 6.25 μm wavelength due to the lack of water vapor absorption at this wavelength, which allows the beam to be transported in air.

An *XY* scanning stage with a sample holder was positioned on an inverted optical microscope (Axiovert 35, Karl Zeiss). A slightly diverging pump beam was transmitted through a glass slide with a shadow mask and focused by the microscope objective [Nikon, 50×, 0.45 numerical aperture (NA), 13.8 mm working distance] to a 200 μm diam circle. The demagnified image (70×) of the mask produced a dark region in the middle of this circle leaving a small opening (TA) in the TM. Different masks were used to produce TAs varying in size from 0.5 to 3 μm.

Pump light reflected from the sample and transmitted through the semitransparent mirror (2) ($T \sim 10\%$) was di-

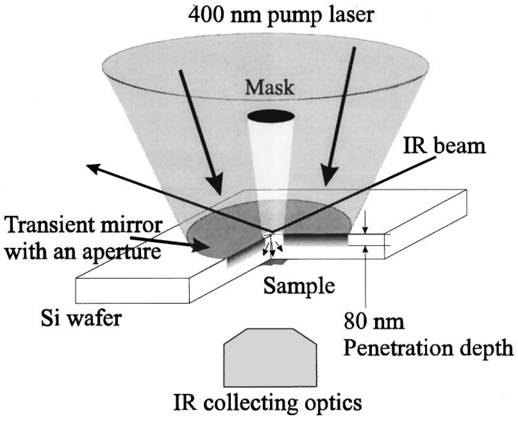

FIG. 1. Concept of a near-field microscope with a photoinduced transient aperture.

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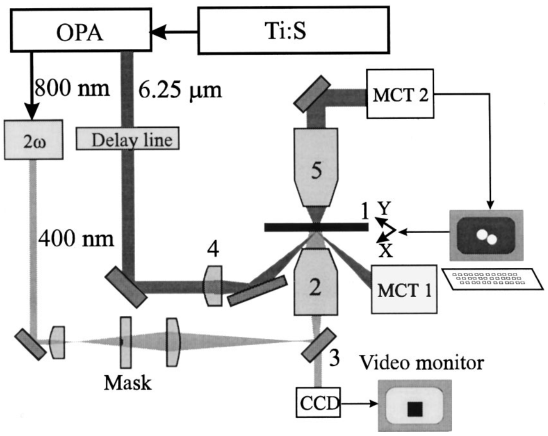

FIG. 2. General scheme of the experimental setup. 1—Scanning stage; 2—visible light microscope objective; 3—semitransparent mirror; 4—IR illuminating optics; 5—IR collecting optics.

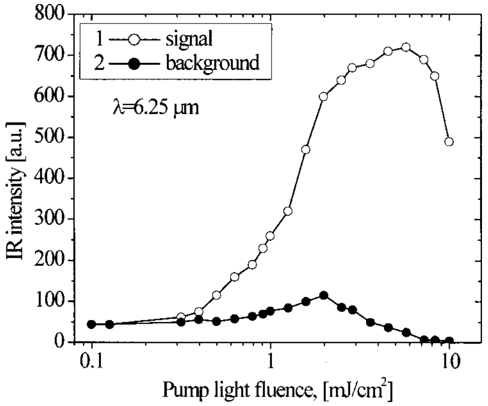

FIG. 4. Transmission of the 1 μm transient aperture at 6.25 μm as a function of pump light fluence.

rected toward a video camera (Panasonic GP-KS162), enabling observation of the object and focusing of the pump beam during the experiment. Infrared light was focused by an $f/10$ focusing system onto the semiconductor surface at a grazing angle of 20°. At this angle no direct light was collected by the reflecting objective (Ealing, 25×, NA 0.4) that was used for near-field imaging. IR light was detected by liquid nitrogen cooled mercury–cadmium–telluride (MCT) detectors (KMPV-50, Kolmar Technologies). MCT1 was used for reflectivity measurements and MCT2 for transmission measurements and imaging. Signals were analyzed with an oscilloscope (TDS 620B, Tektronix) and recorded with a boxcar integrator and a computer data acquisition system (SPM 100, RHK Electronics).

The second harmonic of the Ti:S laser light can be used to induce strong photoreflectivity in many semiconductor materials. One of the best is silicon, since it has a high damage threshold for 400 nm irradiation (>10 mJ/cm^2), a shallow penetration depth (80 nm), and thin layers of Si are transparent to red light allowing conventional imaging of the sample.

The TM lifetime was tested for two types of substrates: 0.5 mm thick Si wafers and 2 μm thick free-standing crystalline Si films. Measurements were performed at pump light intensities two times below the damage threshold, providing mirror reflectivity close to the saturation limit. Depletion of free carriers, which determines the TM lifetime, results from recombination and diffusion. In a thin film, 3D diffusion is limited compared to that in a bulk sample. At the same time one can expect a higher surface recombination rate in a thin film substrate.

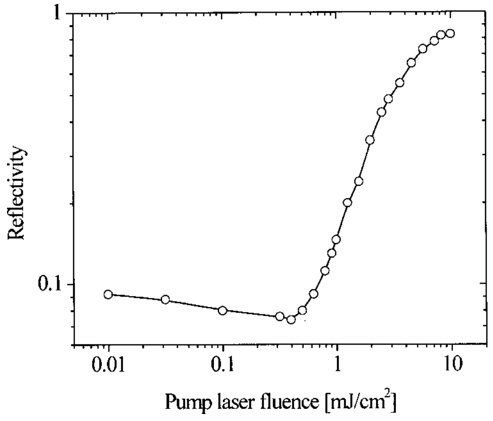

FIG. 3. Transient mirror reflectivity at 6.25 μm wavelength as a function of 400 nm pump light fluence.

Experimental values of lifetimes measured at the $1/e$ level were found to be 40 ps for 2 μm thick Si films and 100 ps for 0.5 mm wafers. Both times are much longer than the OPA pulse duration (1 ps) thus providing stable reflection conditions during the IR pulse.

TM reflectivity as the function of pump light fluence is shown in Fig. 3. The IR laser pulse was delayed with respect to the pump beam by 5 ps, providing the highest TM reflectivity. At lower pump intensities the reflectivity decreases due to the decrease in the refraction index at free carrier densities below the critical density. Above the critical density, reflectivity rises rapidly and reaches saturation at a pump level below the Si damage threshold. This result is in good agreement with theoretical predictions[6] and sets requirements on the contrast of the shadow mask image. A saturated TM with a highly transparent TA can be created if the pump light intensity in the shadow region is less than 10% that in the illuminated area.

The pump light intensity distribution in the microscope focal plane was measured directly with an optical probe. A 0.3 μm diam hole in a 100 nm thick metal screen was scanned in the focal plane, and light transmitted through this hole was detected by a photodiode. The contrast ratio of the image of 1 μm mask was found to be better than 100 and the edge sharpness was better than 0.5 μm. These results are

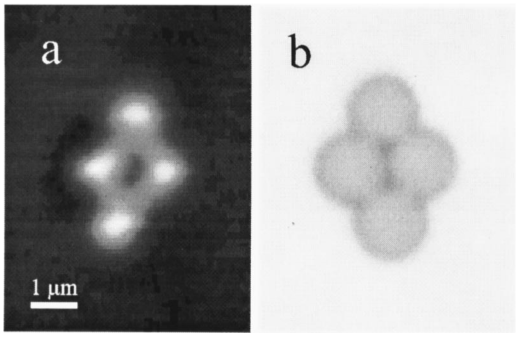

FIG. 5. Images of the four-hole structure in a gold film. (a) Near-field IR image; (b) visible light image obtained with a conventional microscope.

consistent with the diffraction limited resolution of the objective used.

Results of the transmission measurements are presented in Fig. 4. Line 1 shows the signal recorded when the semiconductor surface was illuminated through the shadow mask. This signal consists of the light transmitted through the TA and a background signal, which we believe results from the light scattering from inhomogeneities in the TM. Precise alignment of the IR collecting objective helped to reduce the field of view of the detection system and thus the background radiation. The minimum size of the field of view was set by the diffraction limit and was equal to 10 μm. Line 2 in Fig. 4 represents the background signal recorded at the same illumination geometry, but without the mask. At high pump intensities the background level is reduced and the signal to background ratio for the 1 μm aperture exceeds 100.

As a test object for imaging we used a set of 1.7 μm diam holes in a 200 nm thick gold film on a Si wafer. This structure was prepared by depositing micrometer-sized polystyrene beads on Si, coating it with gold, and then flushing the polystyrene beads away. The Si wafer with the sample structure was raster scanned in the focal plane common for both the illuminating and the detecting systems. With a 1 kHz repetition rate laser system, scanning time was typically 15 s, providing images with 128×128 resolution.

Figure 5(a) shows an infrared image of four adjacent 1.7 μm diam holes. These holes are completely resolved, and demonstrate resolution of better than $\lambda/5$. Figure 5(b) shows the same object obtained with a conventional microscope with white light illumination.

The initial results of near-field microscopy with a transient aperture demonstrate that photoinduced reflectivity in semiconductors can be used to create near-field probes for mid-IR radiation. Resolution of about 1 μm ($>\lambda/5$) was demonstrated. Further optimization of the illumination and detection systems along with methods of substrate preparation should allow for IR imaging of large area samples at near video rates with resolution better than $\lambda/10$.

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