Microscopy and Microanalysis **3**, 815 (1997).

NEAR-FIELD OPTICAL SPECTROSCOPY: ENHANCING THE LIGHT BUDGET

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The near-field scanning optical microscope, or NSOM, provides spectroscopists with resolution beneath the diffraction limit.[1] In the NSOM, an optical aperture smaller than the wavelength λ of the probe radiation is scanned in the near-field of a sample. Pixels are serially gathered and then constituted as a computer-generated image. Spectroscopic NSOM investigations demonstrating sub-λ resolution include studies of photoluminescence, Raman spectroscopy, and single molecule fluorescence. Results of nano-Raman spectroscopy on semiconducting Rb-doped KTP are shown in figure 1. Figure 1a is a topographic image of the sample showing a square Rb-doped region in an otherwise undoped sample. Figure 1c is a NSOM region of the corner of the doped region, and figure 1b is an image of the same region taken within a Raman line. While these data do provide sub-λ spectroscopic resolution and other interesting features[2], the weak signal provided by current NSOM technologies and the low quantum efficiency of the Raman effect necessitated development of a very low-drift microscope and inconveniently long collection times. To make such spectroscopic investigations more convenient, we examined the light budget in NSOM studies.

In typical NSOM investigations, milliwatts of power are injected into an optical fiber, and nanowatts of useful radiation pass through the sub-λ aperture at the other end of the fiber. This aperture at the apex of the tapered end of the fiber constitutes the near-field probe. The throughput, T, of an NSOM taper is a function of three terms. One involves the losses of light in the near-field region of the probe, L_{nf}. Another involves losses in the transition region from the far-field to the near-field, L_{tr}. A third, Θ, marks the damage threshold of the probe: $T = (1 - L_{nf}) \cdot (1 - L_{tr}) \cdot \Theta(P_o/P_d)$. In this expression, Θ is a function of the ratio of the output power of the near-field aperture, P_o, to the damage threshold power P_d. That is, Θ is unity for $P_o < P_d$ and zero for $P_o \geq P_d$ so determines the maximum input power. In typical NSOM operation, six orders of magnitude of losses are split between terms $(1 - L_{nf})$ and $(1 - L_{tr})$, each of which allows only fractions of a percent of the injected power to be available for near-field use. By optimizing taper shape and taper wall reflectivity, throughputs as high as 10^{-4} have been reported.

The inefficiency of the probe does not directly limit the useful power in NSOM investigations, however. Relatively low efficiencies could be tolerated, and higher output power, P_o, would result if an NSOM taper were capable of dealing with higher input powers, i.e. if the damage threshold, P_d, were higher. As the injected power approaches several milliwatts, the damage threshold is surpassed when the probe simply becomes too hot and the metal coating of the taper (typically aluminum) diffuses into lumps, enlarging the effective aperture and rendering the probe useless for sub-λ studies. Typically, output powers of a few nanowatts results in probe damage.

Calculations show that the large majority of the power lost in an NSOM taper is consumed in reflections occuring tens to hundreds of microns from the probe apex.[3] In this region, interactions of the injected light with the probe wall occur at angles shallower than the critical angle for total internal reflection, or TIR. This condition persists until only a few microns from the probe apex, thus the utility of the metal coating comes into question. An aperture is required in NSOM probe to confine the optical field to sub-λ dimensions, so the metal coating must exist in the near-field region.[4] These arguments lead one to an optimized probe design: a tapered optical fiber with a confining metal coating extending only a few microns from the taper apex. A scanning electron microgram, or SEM, of such a fiber is shown in figure 2. The 60 nm thick aluminum coating extends approximately 15 microns from the taper apex. A sub-λ aperture allows for nano-metric NSOM investigations. This probe passed 2 microwatts of power through the near-field region before reaching its damage threshold. Optical micrograms show negligible leakage from the uncoated tapered region. Only minimal scattering is observed where dust particles frustrate TIR. Preliminary spectroscopic NSOM studies using this novel tip design are reported.[5]

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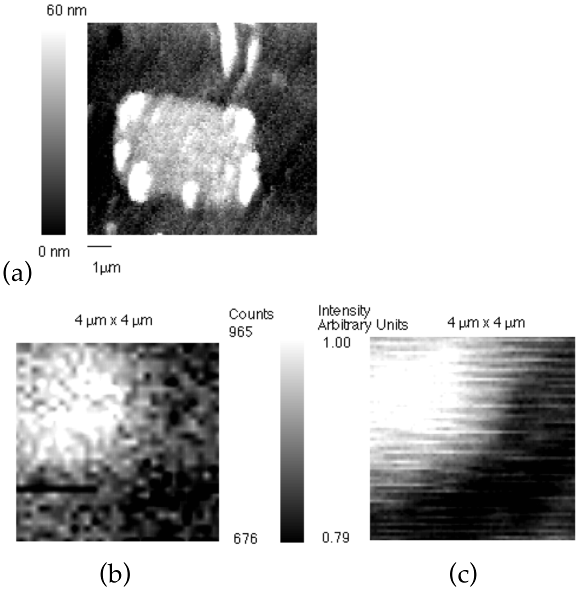

FIG. 1 - NSOM Raman of KTP. (a) is a topographic image (20 µm square) indicating the Rb-doped region. A 4 µm square nano-Raman image (b) taken within a Raman line at 760 cm^{-1}and a NSOM image of a corner of the doped region (c) are also shown.

FIG. 2 - SEM image of improved NSOM tip design. The Al coating extends approximately 15 µm from the apex. where a sub-λ aperture is apparent.