

Infrared Microspectroscopy of Semiconductors at the Diffraction-limit

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Infrared microspectroscopy, using synchrotron radiation as a source, is demonstrated as a tool for exploring semiconductor materials and devices. The synchrotron provides greater brightness than the standard infrared source, enabling an order of magnitude improvement in practical spatial resolution, i.e. approaching the diffraction limit. Since conventional and microscopic infrared spectroscopy are already used for probing semiconductor materials, we expect that the ability to explore sample regions only a few microns in size will be valuable for analyzing materials at dimensions approaching those of many microelectronic devices. Some examples for inclusions in Si and CdZnTe are presented.

INTRODUCTION

Infrared (IR) spectroscopy is a standard probe for semiconductor materials due to its ability to sense electronic properties as well as detect various impurities. In manufacturing, IR spectroscopy can be used to identify contaminants that may appear during device processing. The spectral region between 600 cm^{-1} and 3000 cm^{-1} is often referred to as the "molecular fingerprint region" due to the large number of molecules (both organic and inorganic) that can be differentiated and identified from extensive catalogs of library spectra.

As the dimensions of individual component structures become smaller, device operation becomes increasingly sensitive to microscopic defects and contaminants. IR microspectroscopy has developed into a valuable tool for characterizing such defects, and high performance microspectrometers are now commercially available. In principle, these instruments are capable of analyzing small specimens (approaching the diffraction limit), however the spectrometer's infrared source (typically a $\sim 1200\text{K}$ blackbody) does not possess adequate brightness to achieve acceptable signal-to-noise ratios (S/N) when probing regions much smaller than about $30\text{ }\mu\text{m}$. In contrast, the infrared produced as synchrotron radiation is 2 to 3 orders of magnitude brighter than a blackbody source[1]. To exploit this, an Infrared Microspectroscopy Facility (IMF) has been established at the National Synchrotron Light Source (NSLS) of Brookhaven National Laboratory. A primary component of the IMF

measurement program involves the characterization of various semiconductor materials and devices.

Semiconductor Infrared Properties

A number of important semiconductor properties can be sensed by IR spectroscopy. At long wavelengths ($\lambda \sim 20\text{ }\mu\text{m}$), absorption due to free carriers and phonons occurs, in some cases allowing for quantities such as the carrier density to be determined. The onset of absorption at the band edge is useful for confirming the stoichiometry of alloys such as $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$. Electronic transitions involving dopants or impurities can also be sensed. Even neutral impurities can sometimes be detected through their "local vibrational mode" (LVM) absorption. An important example of the latter is oxygen in silicon[2], which has well-defined absorption modes near $\lambda \cong 9\text{ }\mu\text{m}$ and $\lambda \cong 8\text{ }\mu\text{m}$, depending on whether the oxygen is located at an interstitial site or in the form of an oxide, respectively. Another technically important semiconductor is GaAs, for which a variety of local vibrational modes, corresponding to important dopants and impurities, have been catalogued[3].

Synchrotron Infrared Microspectroscopy

The brightness limitation of the conventional source in IR microspectroscopy is alleviated by the use of infrared synchrotron radiation (IR-SR) as the source. We have installed a commercial IR microspectrometer (a Spectra-Tech "IR μs "TM) at beamline U2B of the NSLS[4] and

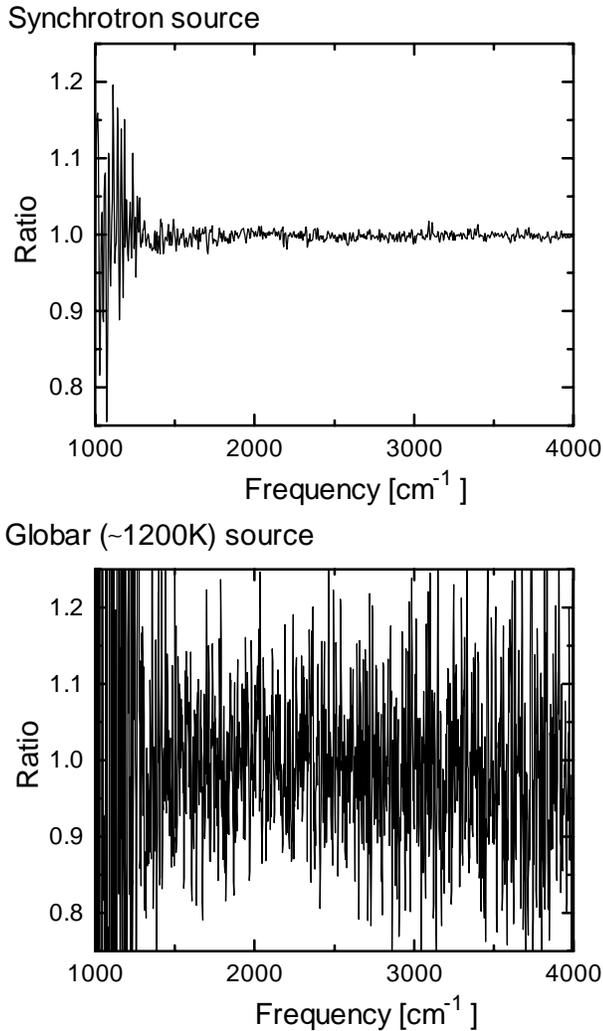


Figure 1. Noise comparison of the synchrotron and globar infrared sources for a 3 μm aperture.

tested its performance[5]. The high source brightness enables good S/N even when probing regions smaller than 10 μm in size. Figure 1 shows a comparison of the S/N for the IR-SR and globar sources when the infrared sampling area is limited by a 3 micron diameter aperture. The data represents the ratio of two sequential transmission measurements, and in the ideal case (no noise or drift) would be a perfectly smooth line at unity. Note that the synchrotron source is capable of spectroscopy for frequencies down to nearly 1400 cm^{-1} , which is a wavelength ($\lambda \approx 7 \mu\text{m}$) more than twice the size of the aperture. This demonstrates the synchrotron source's potential for exploiting near-field techniques that could extend the spatial resolution beyond the diffraction limit.

MEASUREMENT & ANALYSIS

The IMF has been used to map oxygen variations (which includes differentiating interstitial atoms from oxide precipitates[2]) in silicon, and for probing the regions around micron-sized Te precipitates in $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ wafers. The IR μs^{TM} includes a scanning stage to allow for automatic mapping of spectra over a pre-defined area.

Silicon

Figure 2 shows the IR transmission of two silicon wafers. The $\lambda = 9\mu\text{m}$ (1110 cm^{-1}) absorption due to interstitial oxygen is present to some degree in most wafers[6]. One

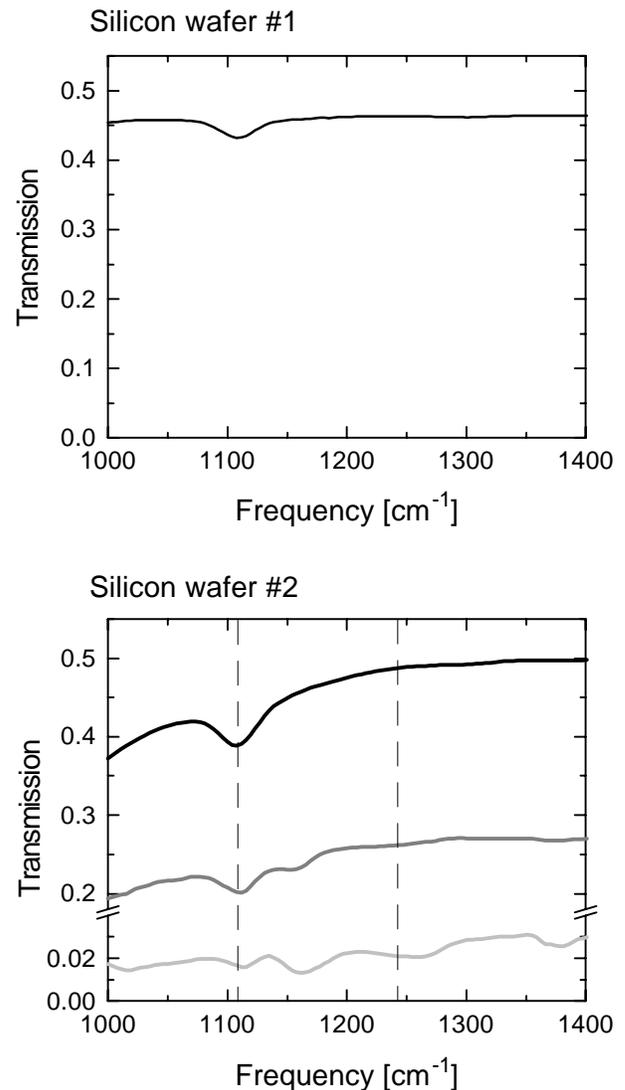
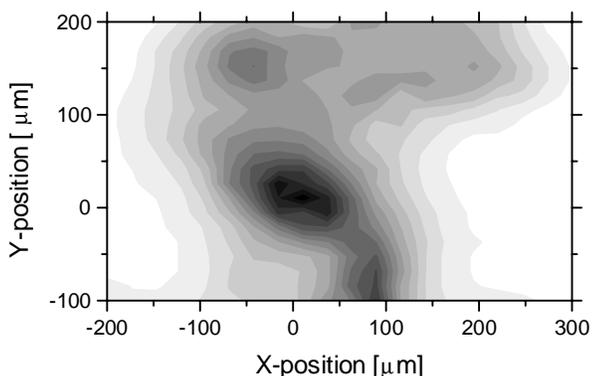


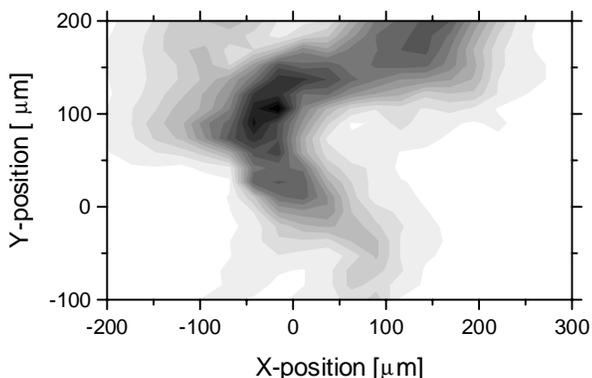
Figure 2. IR transmission for two silicon wafers. The lower panel shows spectra near a major defect. Vertical dashed lines mark two of the oxygen mode frequencies.

particular piece of silicon had a major sub-surface defect (not visually detectable), and a region around the defect was spectroscopically mapped. Transmission spectra for three locations at, and near, the defect are shown in the lower panel of Figure 2.

Overall absorbance



$\lambda=9\mu\text{m}$ (1110 cm^{-1}) absorbance - interstitial oxygen



$\lambda=8\mu\text{m}$ (1240 cm^{-1}) absorbance - oxide

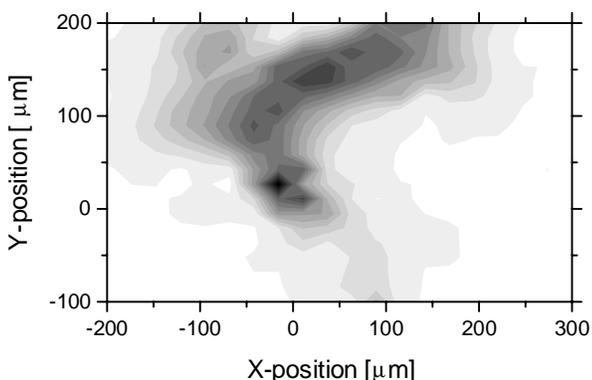


Figure 3. Silicon wafer absorbance maps at three different wavelengths (chosen to differentiate the type of oxygen) for the region surrounding a sub-surface defect. Darker shading indicates higher absorption.

Full IR spectra were then collected at $25\mu\text{m}$ intervals over a rectangular area surrounding the defect, and the absorption at selected wavelengths was extracted. Contour maps of the absorption are shown in Figure 3. Note that the distribution of oxide and oxygen interstitials are similar, but not identical.

$\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ (CZT)

CZT is a substrate material for II-VI semiconductor devices, such as the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ (MCT) photodiode arrays used in long-wavelength IR imaging systems. Growing high quality CZT crystals is difficult, and it is not entirely clear what defects are specifically responsible for poor array performance. Tellurium precipitates are one commonly encountered defect, but their affect on the local electrical and chemical environment is not well understood. We have begun to investigate these $\sim 5\mu\text{m}$ sized inclusions by IR microspectroscopy. The transmission (relative to a clear section of CZT) is shown in Figure 4. Diffraction of light around the

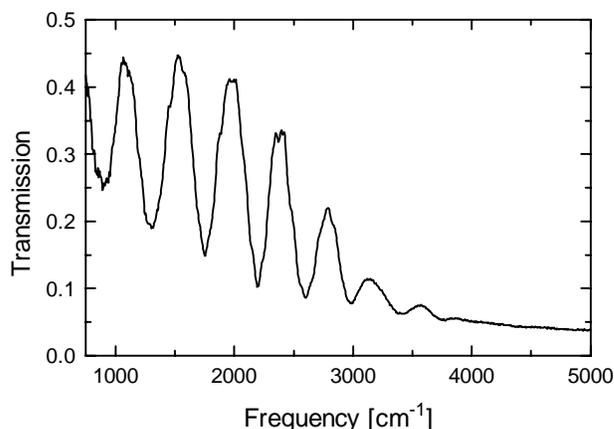


Figure 4. The transmission through a single Te precipitate buried near the surface of a CdZnTe wafer crystal. The IRμs apertures were set to sample a $5\mu\text{m}$ square area, approximately matching the size of the precipitate.

precipitate is partly responsible for the increasing transmission at long wavelengths. Also visible are broad interference fringes for wavelengths greater than $3.5\mu\text{m}$, which corresponds to the bandgap for bulk Te. The fringe spacing is consistent with a diameter of $4\mu\text{m}$ and a refractive index between 2.5 and 3.0. Contour maps of the absorption at two wavelengths (spanning $\lambda_g = hc/E_g$ of Te, for material contrast) are shown in Figure 5. These maps were extracted from approximately 180 complete spectra, acquired at $10\mu\text{m}$ intervals over a

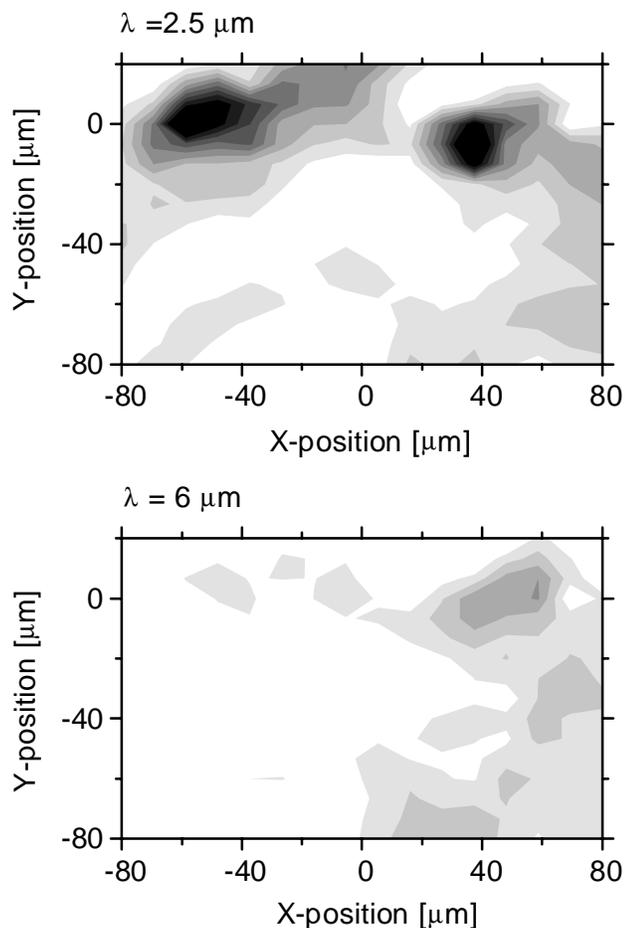


Figure 5. Absorbance maps of a CdZnTe wafer in the vicinity of two Te precipitates. *Upper panel:* for $\lambda=2\mu\text{m}$. *Lower panel:* for $\lambda=6\mu\text{m}$. Darker regions represent higher absorbance. The same absorbance gray-scale was used for both panels.

rectangular region of a CZT wafer section. Other regions of less (but non-zero) absorption are also visible.

SUMMARY

The synchrotron radiation source extends the spatial resolution of infrared microspectroscopy to a size scale approaching a few microns. The IMF will continue to be developed and utilized for studies of semiconductor materials and devices. Much of our effort will be directed toward compound and alloy semiconductor systems, including materials and devices for infrared focal plane arrays. Of particular interest will be correlating localized defects with specific device failure mechanisms.

Other features of the infrared synchrotron source, such as the high degree of polarization and the sub-nanosecond pulse duration, are maintained by the IR microspectrometer, though they have not been exploited for the measurements presented here. The strong polarization should prove valuable for grazing-incidence reflection studies of the absorption by very thin layers, such as the gate oxides in silicon MOSFETs. The pulses are useful for time-resolved measurements, such as determining the intrinsic speed of a detector material, or for pump-probe spectroscopy[7].

Finally, synchrotron IR microspectroscopy allows entry into *near-field* techniques that could extend the spatial resolution beyond the diffraction-limit. The work here demonstrates that a $3\mu\text{m}$ spatial resolution can be achieved, and improvements to eliminate aberrations from the present beamline mirror system could enable $1\mu\text{m}$ spatial sensitivity to be realized. To reach another order of magnitude beyond that will almost certainly require a much brighter source of tunable infrared photons, such as the IR free electron laser.

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