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THERMAL-OPTICAL SWITCHING OF A SILICON BASED INTERFERENCE FILTER

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We report thermal-optical switching using a silicon based interference filter fabricated by plasma enhanced chemical vapor deposition. A five film structure using high index films of amorphous Si and low index films of SiO_2 comprised the device which yielded detector limited 40 ns rise time switching. Operation is in the near infrared spectral region with probe wavelengths of 810 nm and 1.152 μm. A 56% contrast ratio is reported when pumped by a 10.6 μm CO_2 pulsed laser. Lower contrast switching was also demonstrated with a Nd:YAG pumped dye laser tunable from 600 - 700 nm. In addition we have demonstrated that atomic layer thickness precision is not necessary, and suggest several improvements which can further enhance device performance.

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There has been considerable interest in recent literature on the design and fabrication of optical devices for photonic switching. Many different approaches to optical logic have been employed including bistable etalons[1], semiconductor waveguides[2], and most recently multiple quantum well (MQW) devices[3]. Although offering many performance advantages, MQW devices require atomic growth precision made possible using fabrication techniques such as molecular beam epitaxy (MBE) or metal organic chemical vapor deposition (MOCVD) which are slow and not suitable for routine processing. Also the MQW structures are generally fabricated with more than twenty-five ultra-thin layers of semiconducting materials such as GaAs and AlGaAs which are not easily integrated with ubiquitous silicon based electronic circuitry. Picosecond thermal optical switching using multiple film ZnSe based interference filters has been

reported.[4,5,6] These require less precise thickness control, but are also difficult to fabricate and not compatible with silicon circuitry. In addition, these devices operate in the visible spectral region away from fiber optic transmission between 1.3 μm and 1.5 μm in the near IR. While demonstrating efficient device performance, these approaches have been unable to resolve the dilemma of integration of optical devices with silicon electronic materials. With these issues in mind we have designed, modeled and fabricated an interference filter operating in the near infrared spectral region using alternating thin films of Si and SiO_2 that were deposited by plasma enhanced chemical vapor deposition (PECVD).

An interference filter is a series of alternating high and low refractive index dielectric films, with film thickness, L, given by:

$$L=\frac{m\lambda}{4n} \qquad (1)$$

where λ is a chosen center probe wavelength, n is the refractive index of the film, and m is an odd integer order. The optical thickness, nL, is equal to an odd multiple of the quarter-wave of the probe wavelength. These quarter-wave films are grown symmetrically about a center spacer layer grown to a multiple half-wave of the probe wavelength. This design results in efficient transmission of the probe, but reflection of other wavelengths. Switching occurs by changes in the nonlinear refractive index, the thermal-refractive effect, or in thermal expansion brought about by absorptive heating.[4]

We have designed and fabricated a five film interference filter using hydrogenated amorphous Si, a-Si:H, as the high index layer and SiO_2 as the low index layer. Both materials were deposited by PECVD on a 4" fused silica substrate resulting in uniform, high quality optical films. Refractive indices of 3.64 and 1.449, respectively, were measured at 1.152 μm using infrared ellipsometry. The quarter-wave layers were grown to order m = 3, and the half-wave spacer layer was grown to order m = 9. This was done to provide a thicker Si layer for absorption, and to sharpen the bandpass of the device. A 1.152 μm center probe wavelength was chosen. Figure 1 shows a comparison of the near infrared Fourier transform (FTIR) spectra from 800 - 1300 nm and the bandpass calculated from the layer thickness measurements made during deposition. There is qualitative agreement in both FWHM and intensity of the peaks, although the actual peak positions are blue shifted by approximately 50 nm. This difference is attributed to errors of several percent in the estimated film thickness during deposition, and the refractive index. A 0.8% change in optical thickness of the spacer layer will generate the 50 nm shift in peak position which translates to ± 0.03 in the refractive index, or 11.4 nm in thickness of the spacer layer. These are within the error estimates of both the thickness and index measurements, and account for the difference of the calculated and FTIR spectra. Another error is due to dispersion since the index measurement used in the model was made at only one wavelength.

In addition, we have modeled and observed the effect of deviations in film growth thickness from the desired quarter-wave or half-wave conditions. We found that random errors not exceeding 5% tend to cancel and are tolerable. The bandpass center wavelength is shifted by less than 20 nm, but can be recovered by changing the angle of incidence of the probe beam. However, if the films are grown with an error of more than 5% from the desired thickness, and all of the films have the same error trend, that is either too thick or thin, then the transmission peak can be shifted by 50 nm or more, and would require more than 30° on angle of incidence to tune the transmission maximum. Actually, all of the device films were thicker than desired, with an average film error of 5% for all but the top film which was 298.0 nm, or 26% thicker than desired. Despite this large error, the filter maintained a 10 nm bandpass with the peak shifted by only 15 nm as shown in figure 1.

The switching configuration consists of a pump and a probe laser. The probe is a CW laser tuned to a transmission maximum determined by FTIR, and the pump is a pulsed laser. We have performed switching experiments with both the peak at 820 nm and at 1.167 μm using an AlGaAs diode laser at 810 nm and a HeNe laser at 1.152 μm for the probes. The transmission resonances are tuned by changing the angle of incidence of the device with respect to the probe laser. Pump wavelengths included a 10.6 μm CO_2, a 1.064 μm Nd:YAG, a frequency doubled Nd:YAG at 532 nm, and a Nd:YAG pumped dye laser operating from 600-700 nm.

The CO_2 pumped device resulted in a 56% contrast ratio using the 1.152 μm HeNe probe laser. Contrast ratio is expressed as a percentage of the total maximum transmission intensity compared to the switched out intensity. Threshold switching energy was 5.5 mJ. With a 1 MΩ input to the scope, the device had a fast rise time of 17 μs, but a slower fall time of 175 μs that was limited by thermal diffusion. When the pump laser spot size was reduced using an aperture to slightly larger than the probe laser spot size, the diffusion tail could be reduced by an order of magnitude when compared to a spot with no size reduction. This did not affect the rise time of the device. Figure 2 shows the trace of the switched out signal with a 1 MΩ input into the scope with an aperture to reduce the pump laser spot. The larger spot size results in a greater heated area with thermal diffusion being responsible for the slow fall time.

The dye laser pumped device with the 1.152 μm HeNe probe resulted in only 11% contrast ratio at an energy of 8 mJ / pulse. This yielded a detector limited 40 ns rise time with a 50 Ω input into the scope. Again the 20 μs fall time was limited by thermal diffusion, and was not optimized for overlapping beam spot sizes. We were able to generate both a positive and negative signal depending on initial tuning, indicating that the switching was not due to increasing absorption of the probe laser. Neither the Nd:YAG laser at 1.064 μm, nor the frequency doubled 532 nm pump wavelengths resulted in switching.

Switching occurs by two different mechanisms as elucidated using the CO_2 and the

Nd:YAG pumping. The CO_2 laser at 10.6 μm excites phonon modes in both the a-Si and the SiO_2 layers. This results in thermal expansion of the films and the bandpass resonance no longer being satisfied. The absorption coefficient, k, at 10.6 μm is 0.2 and 1×10^{-3} for the SiO_2 and the a-Si films respectively.[7] Only considering absorption in the films, the SiO_2 layers attenuate the pump excitation more efficiently than the Si films. In addition, the fused silica substrate contributes to absorption of the CO_2 pump laser yielding a 56% contrast ratio. On the other hand, the Nd:YAG pumping generates free carriers only in the a-Si layers. This then results in a positive feedback loop of increasing temperature, leading to increasing absorption known as the thermal-refractive effect.[8] We believe that the pump at 1.064 μm is not sufficiently absorbed by the a-Si to generate an optical thickness change. It is well known that PECVD produces hydrogen rich amorphous Si (a-Si:H) with band-tailing of states in the band gap. The concentration of hydrogen and of dangling bonds strongly affects the number of these states and hence the absorption coefficient.[7] Assuming that the absorption coefficient is close to that of c-Si (5.8×10^{-4}), the spacer layer, which is 1.45 μm thick, will only attenuate 1% of the pump intensity. This is not sufficient to effect an optical thickness change. The absorption coefficient varies by orders of magnitude for amorphous Si at the band edge.[9,10,11] The technology of a-Si film deposition attests to process parameter sensitivity of the bulk states which can significantly alter the optical absorption. We believe that our a-Si films have an absorption coefficient close to that of c-Si, and thus do not attenuate the pump irradiation sufficiently to induce a thermal-refractive effect.

Conversely, too much absorption in the top Si film results in no switching with the 532 nm pump. The absorption coefficient at 532 nm is approximately 1.[7] The top Si film, which is 0.295 μm thick, absorbs 99% of the pump irradiation. Previous literature has indicated that the largest switching effect is from index or thickness changes in the spacer layer.[4] Essentially, the 532 nm pump light is not transmitted sufficiently to the spacer layer to effect switching. The 640 nm wavelength with an absorption coefficient of 2×10^{-2}, sufficiently transmits through the top Si layer (almost 75%), and nearly completely absorbs in the spacer layer, thereby yielding a significant switching effect.

In an effort to relate the magnitude of switching for both the CO_2 and the dye pumped devices to the reported contrast ratios, estimates of the effective change in the position of the transmission maximum peak after pump excitation were made. This was accomplished by switching the device optically as previously described. We then simulated the switching experiment by manually rotating the sample stage to determine the angle, θ, that would give an equivalent intensity change as induced by the pump laser. Figure 3 shows the calculated transmission maximum peak position as a function of the angle of incidence of the probe laser. We found that the CO_2 switched intensity change was equivalent to a physical change in angle of incidence, θ, of 5.65°. Similarly, at 640 nm, θ was 1.85°. These values correspond to transmission maxima changes, ΔT, of 5.9 nm and 0.9 nm, respectively. Figure 4 shows the FTIR spectra of the 1.167 μm transmission peak with a FWHM of 10 nm. A 5.9 nm change in transmission position results in a 53% change in transmission intensity, and a 0.9 nm change results in a 6%

change in intensity. This compares favorably to the measured contrast ratios for the two frequency pump sources of 56% and 11%.

One can sharpen the FWHM of the transmission bandpass by depositing more films. This increases the finesse of the cavity. We have modeled a nine film device again using Si as the high index layer and SiO_2 as the low index layer. This device shows a 95% transmissivity at the probe wavelength and nearly 0% transmissivity at other wavelengths with a FWHM of 0.75 nm. Since the dye pumped change in transmission, ΔT, was estimated to be 0.9 nm, this device should have nearly 95% contrast ratio while requiring 5% growth precision, and lower energy pump sources. This is compared to the tenth nanometer growth precision demanded by MQW devices. It should also be noted that the films can be grown asymmetrically about the spacer layer with the top films being grown to order m = 1, and the bottom films having a higher order number without significantly affecting the bandpass of the device. This design reduces the attenuation of the pump laser in the quarter-wave layers, and maximizes carrier generation in the spacer layer where most of the switching effect is realized.

We have demonstrated that optical devices can be fabricated from existing microelectronics deposition techniques, one of which is plasma enhanced chemical vapor deposition (PECVD) using Si based materials. These devices enable integration with Si electronic circuitry, can be fabricated by batch wafer processing, and operate in the near IR spectral region. Also this device requires less thickness precision than MQW's, and fewer films than the analogous ZnSe based device. Further improvements include more quarter-wave films and asymmetric growth of the quarter-wave layers about the spacer layer. These changes should sharpen the bandpass and result in higher contrast, lower energy switching.

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LIST OF FIGURES:

Figure 1: Near infrared Fourier transform spectrum at normal incidence (solid line) of a five film interference filter device fabricated from alternating layers of PECVD a-Si and SiO_2 (200 scans at 8 cm^{-1} resolution). The dashed spectrum is the calculated spectra bandpass. The vertical dashed lines indicate several probe laser wavelengths.

Figure 2: Trace of interference filter switching tuned at the initial transmission maximum of a 1.152 μm CW HeNe probe laser and pumped by a 10.6 μm pulsed CO_2 laser.

Figure 3: Calculated change in peak position versus angle of incidence for the five film interference filter. The Si refractive index used was 3.64, 1.449 for SiO_2 film, and 1.50 for the fused silica substrate. Also shown is the equivalent angle of incidence after pump laser excitation.

Figure 4: FTIR spectra of the 1.167 μm peak of the interference filter with a bandpass of 10 nm FWHM.

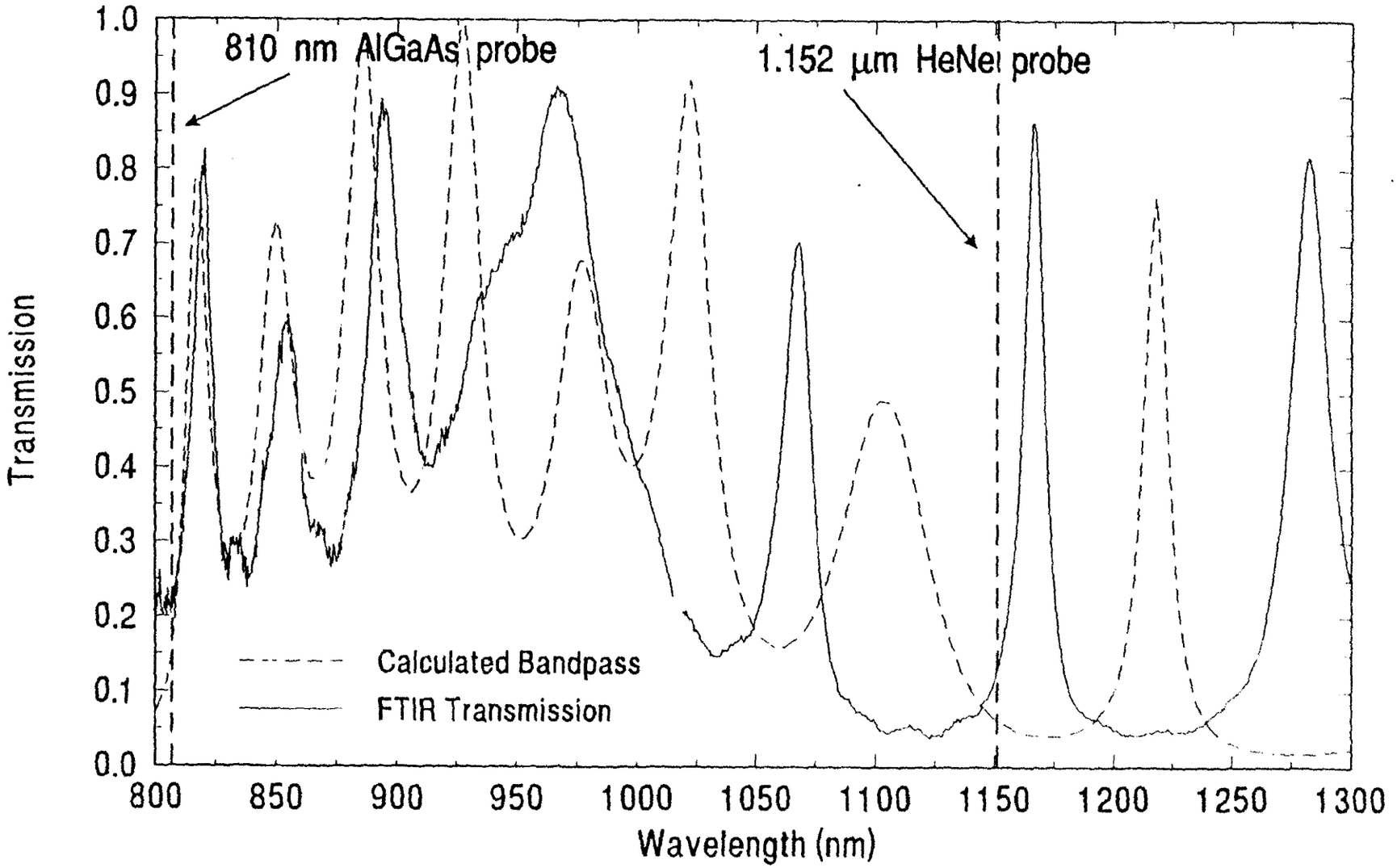
810 nm AlGaAs probe
1.152 µm HeNe probe
Calculated Bandpass
FTIR Transmission
Transmission
Wavelength (nm)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
800
850
900
950
1000
1050
1100
1150
1200
1250
1300

FIGURE 2

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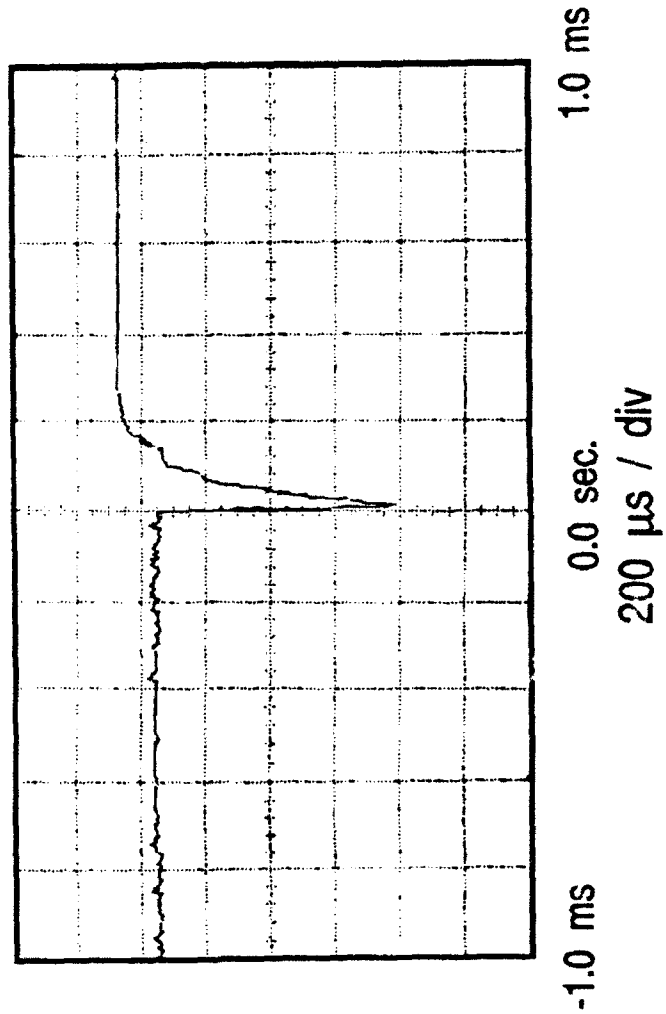
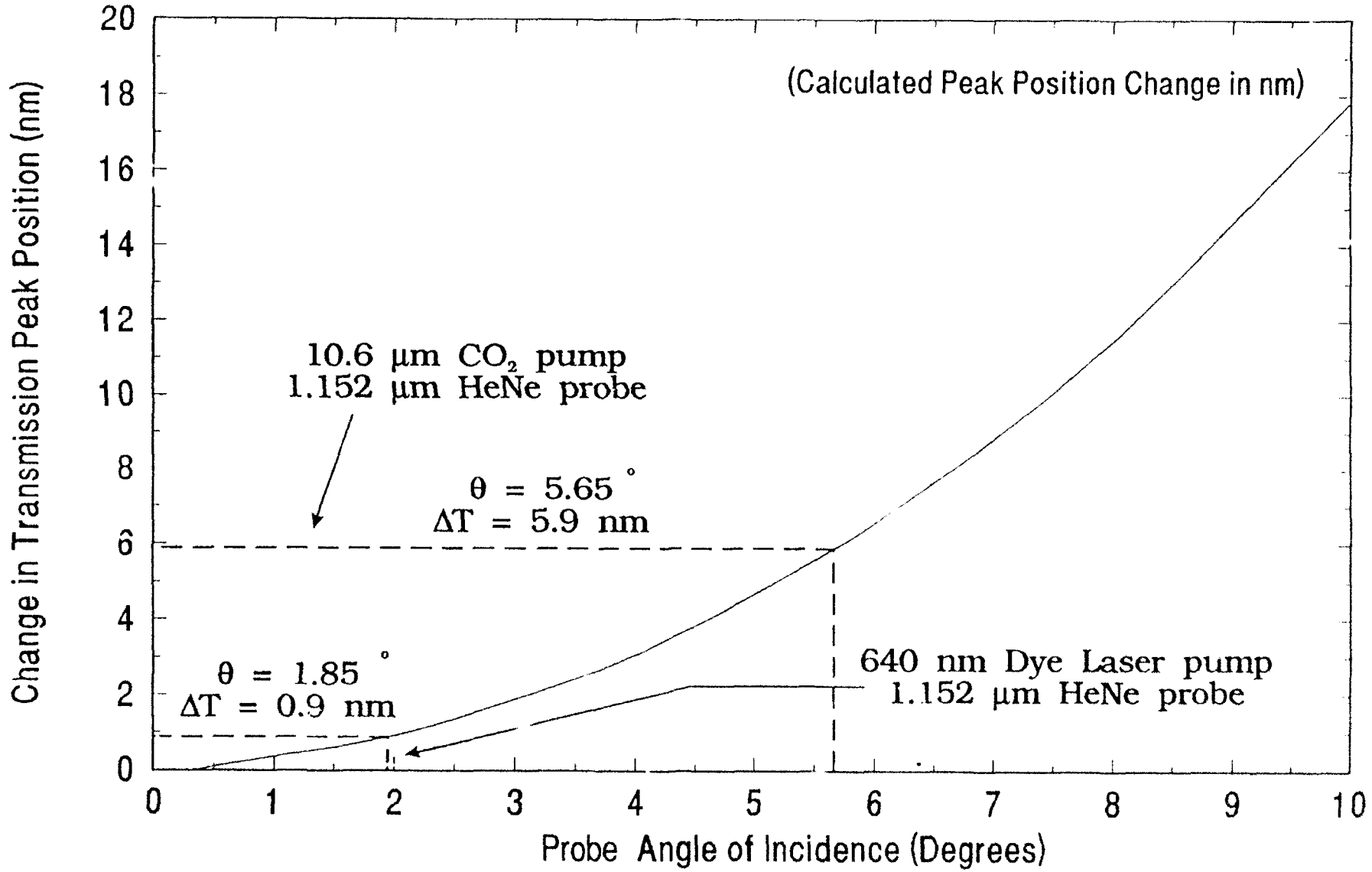
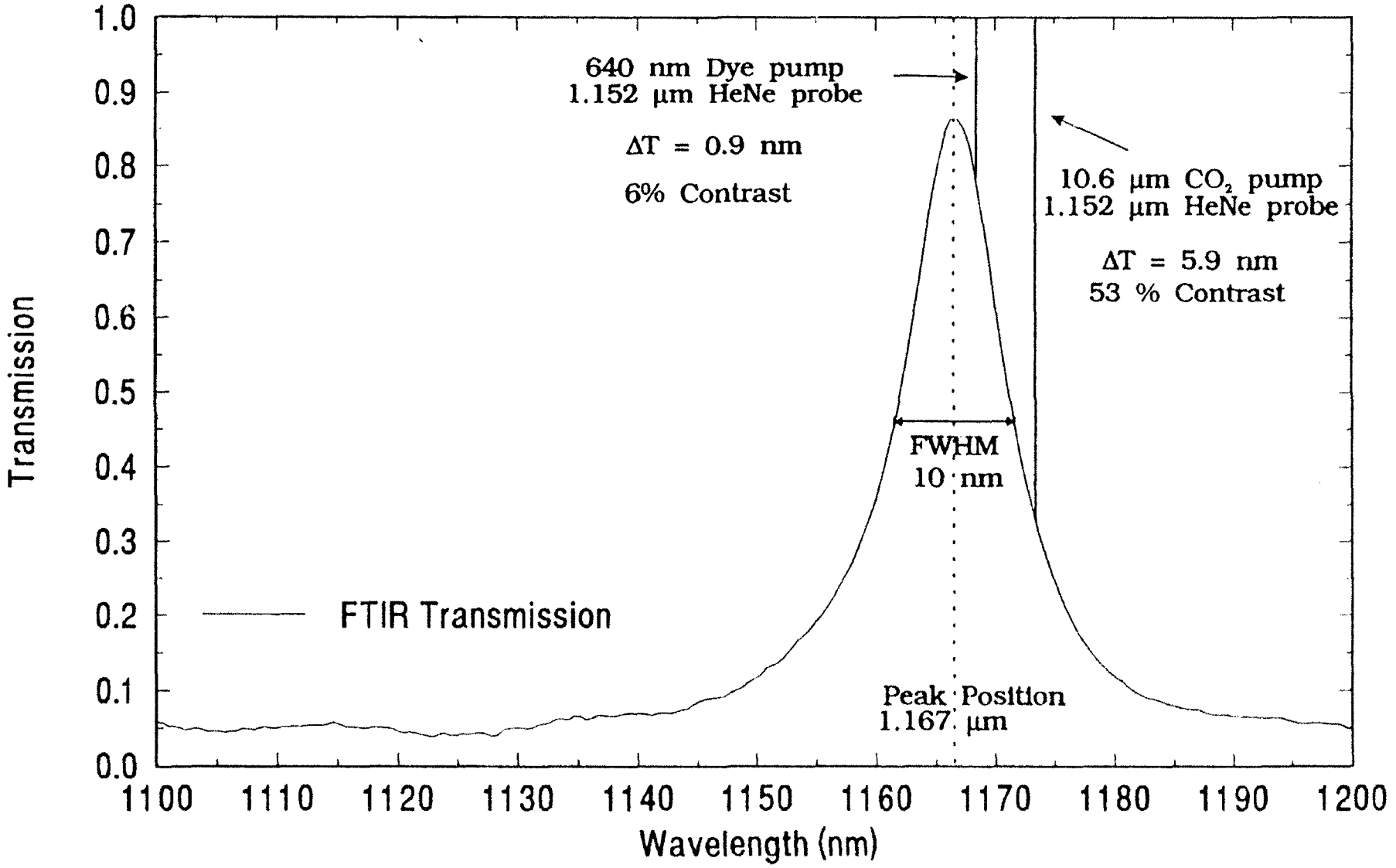



(Calculated Peak Position Change in nm)
Change in Transmission Peak Position (nm)
Probe Angle of Incidence (Degrees)
10.6 μm CO_2 pump
1.152 μm HeNe probe
θ = 5.65 °
ΔT = 5.9 nm
θ = 1.85 °
ΔT = 0.9 nm
640 nm Dye Laser pump
1.152 μm HeNe probe
0
2
4
6
8
10
12
14
16
18
20
0
1
2
3
4
5
6
7
8
9
10


640 nm Dye pump
1.152 μm HeNe probe
ΔT = 0.9 nm
6% Contrast
10.6 μm CO_2 pump
1.152 μm HeNe probe
ΔT = 5.9 nm
53 % Contrast
FWHM
10 nm
Peak Position
1.167 μm
FTIR Transmission
Transmission
Wavelength (nm)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1100
1110
1120
1130
1140
1150
1160
1170
1180
1190
1200