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NONLINEAR OPTICAL ABSORPTION IN INTRINSIC STARK EFFECT SUPERLATTICES

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We have investigated the nonlinear optical properties of a new class of strained-layer superlattices, the intrinsic Stark effect superlattices (ISES). The superlattices consisted of GaInAs/GaAs grown along the (211)B direction. We observed a shift of the excitonic absorption to higher energies (blue shift) with increasing intensity of the transmitted beam. The observed optical nonlinearity was one order of magnitude stronger than the one due to excitonic screening in the (100) oriented reference material. This effect is attributed to the screening of the internal electric fields by photogenerated carriers.

Strained-layer superlattices (SLS) grown with III-V semiconductors along a crystalline direction other than (100), e.g. (111) or (211), show a unique behaviour, beacause the strain between wells and barriers and the piezoelectric effect generate electric fields of opposite polarity in the wells and the barriers (intrinsic Stark effect superlattices, ISES). Fields above 10^5 V/cm have been theoretically predicted.[1,2] These fields are not present in material grown along the (100) axis and in lattice matched superlattices.[3] Most superlattices to date have been grown along the (100) direction.

GaInAs/GaAs SLS have been grown along the (111)[4] and the (211) axis. Linear optical experiments verified the existence of the internal fields[5,6] and electrooptic experiments have been done.[7] Photoluminescence and Raman experiments have shown the effect of internal fields in (111) GaSb/AlSb superlattices.[8] Time-resolved spectra and photoluminescence gave evidence of piezoelectric fields in CdS/CdSe superlattices.[9]

The internal electric fields modify the bandstruccture, alter the transition energies and the matrix elements. Very high nonlinear optic and electrooptic coefficients have been predicted.[10]

In this paper we will discuss the nonlinear optical absorption of the ISES. Electrons and holes generated by illumination are spacially displaced from each other by the internal electric field (see fig. 1a). They generate an electric dipole field opposite to the intrisic field screening the piezoelectric field (see fig. 1b). The energy of the fundamental transition is increased in the screened case (blue-shift).

The GaInAs/GaAs SLS used in this study were grown by MBE on a (211)B surface of a Si-doped GaAs substrate. They were grown on a Te-doped buffer and an 250 nm undoped layer and consist of 10 periods of 7 nm GaInAs wells with 15% Indium content and 14 nm GaAs barriers. They were capped by a 250 nm undoped GaAs layer and a Be-doped cap layer. A reference sample with the identical

structure was grown along the (100) axis. The layer thickness was held well below the critical thickness.[11] The sample quality was controlled by transmission electron microscopy (TEM)[12] and the strain condition was shown to be that of a superlattice matched to GaAs. The material showed a clear excitonic absorption peak at room temperature.

We used a cw Ti:sapphire laser, pumped by an Ar-ion laser, to perform the nonlinear absorption experiment. The sample was cooled to 10 K to avoid heating effects. The pump beam was focused on the sample surface to a spot larger than the one of the probe beam. The transmitted probe beam was detected by a Si-photodiode and processed by a lock-in amplifier.

The (100) and the (211)B material has, as we had predicted, very different nonlinear optical properties. Fig. 2 shows the probe laser transmission as a function of the wavelenght for several laser intensities. If the intensity of the incident laser beam was increased, the excitonic peak of the (100) material remained at the same wavelength and became weaker, as expected due to the screening of the exciton (shown in fig. 2a). However, as can be seen in fig. 2b, the excitonic absorption peak of the (211)B sample showed a distinct shift towards shorter wavelenghts (blue-shift) as the laser power was increased. Additionally the excitonic absorption increased by more than 50%. Both effects can be attributed to the screening of the piezoelectric fields in the wells by photoexcited carriers: when the total field is reduced, the transition enery increases, and the overlap between the electron and hole wave functions increases producing a larger transition matrix element.

To quantitatively determine the optical nonlinearity caused by the screening of the intrinsic fields, we used an absorption modulation technique with pump and probe beam chopped at different frequencies, and we directly obtained the change of the optical transmission caused by the modulated

pump beam. Fig. 3 shows the nonlinear transmission spectra. The modulated transmission of the (100) sample (taken with a pump intensity of 50 W/cm^2 and a probe intensity of 5.6 W/cm^2) shows a single, sharp, positive line of about 0.4% of the total transmission (as can be seen in fig. 3a). This signal can be attributed to excitonic screening by photoexcited carriers. In contrast, the nonlinear transmission signal of the (211)B material (as shown in fig. 3b, taken at pump and probe beam intensities of 176 W/cm^2 and 177 W/cm^2) behaves very differently. It has the derivative lineshape of a shift in absorption, rather than the one of an decrease in absorption. This clearly indicates the blue-shift of the excitonic resonance. Comparing fig. 3a and b one can easily see that the magnitude of the optical nonlinearity of the (211)B material is one order of magnitude larger than the one in the (100) material, namely about 4%. TEM and photoluminescence studies on these samples showed that they both were of similarly good quality. Both samples had the same carrier lifetime of 1 ns.[13] Therefore a difference in the carrier lifetime can be ruled out as explanation of the different optical nonlinearity. From these experiments it is evident that the optical nonlinearity from the screening of the piezoelectric fields is about one order of magnitude larger than the one due to excitonic screening. It should be noted here that at very high excitation inten-sities the nonlinear signal is similar in shape and magnitude to the one of the (100) material. This indicates that in the high excitation regime the internal field is fully screened and excitonic screening becomes effective.

Fig. 4 depicts the spectral position of the peak of the modulated transmission signal (as shown in fig. 3b) of the (211)B material as a function of the incident power density of the transmitted beam while the intensity of the modulating beam was kept constant. The blue shift for laser intensities from

8 W/cm^2 to 2 kW/cm^2 was about 10 nm. Most of the shift was observed at lower to intermediate power levels.

In conclusion, we performed non-linear absorption experiments on GaInAs/GaAs superlattices grown along the (211)B direction with (100) grown material as reference. Our results confirm the existence of piezo-electrically created fields in this material. A strong blue-shift (10 nm) and an increase of the excitonic absorp-tion peak was observed with increasing light intensity . This results directly from the screening of the internal electric fields by photoexcited carriers. The optical nonlinearity from this effect has been shown to be one order of magnitude larger than the nonlinearity due to excitonic screening.

This combination of the blue-shift with the strong nonlinear optical effect and with a fast response time makes the intrinsic Stark effect superlattice an excellent material for applications such as all-optical switching and modulation, integrated optic and phase conjugation.

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Fig. 1 Schematic band diagram of an intrinsic Stark effect superlattice embedded in a p-i-n structure.
a) without illumination, E_o denotes the fundamental transition.
b) with the internal field screened by excess carriers, E_s indicates the transition energy when the internal field is screened.

Fig. 2 Absorption spectra taken at various intensities of the incident beam. All spectra are displayed in the same scale (vertically displaced only).
a) (100) material.
b) (211)B material.

Fig. 3 Modulated transmission spectra
The units of the vertical scale are the same for a) and b).
a) (100) material.
b) (211)B material.

Fig. 4 Spectral position of the peak of the modulated transmission signal of the (211)B sample (as in fig. 3) as a function of the incident power density of the transmitted beam.

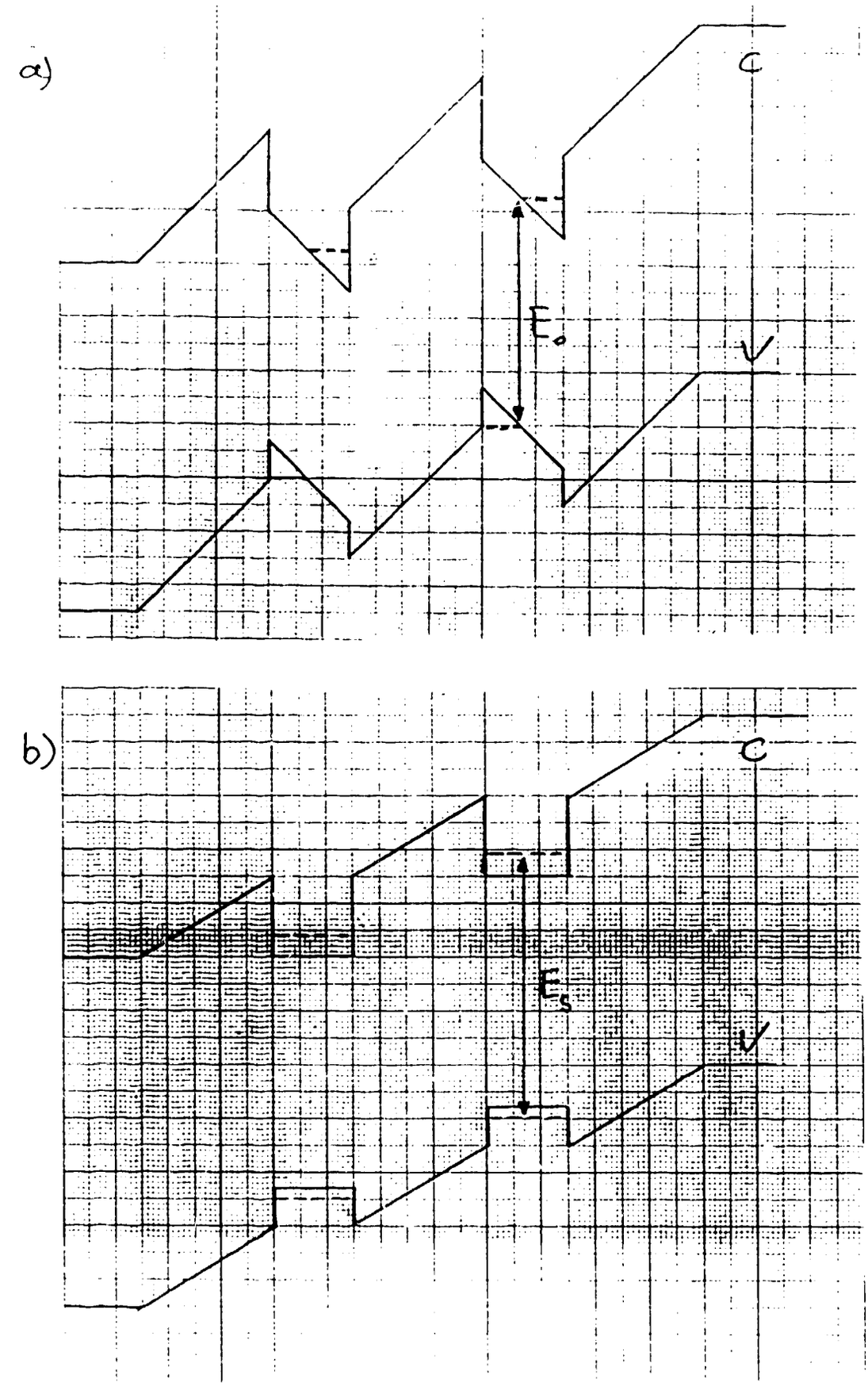
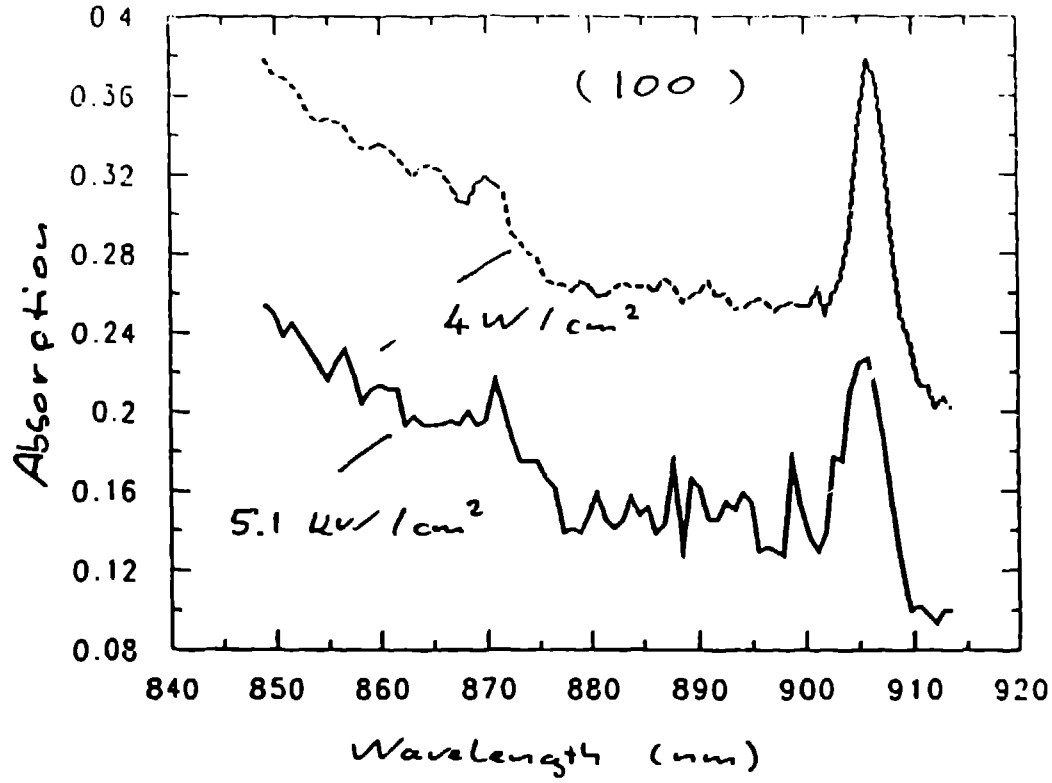


Fig 1

a)


(100)
4 kW/cm²
5.1 kW/cm²
Absorption
0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
840
850
860
870
880
890
900
910
920
Wavelength (nm)

b)

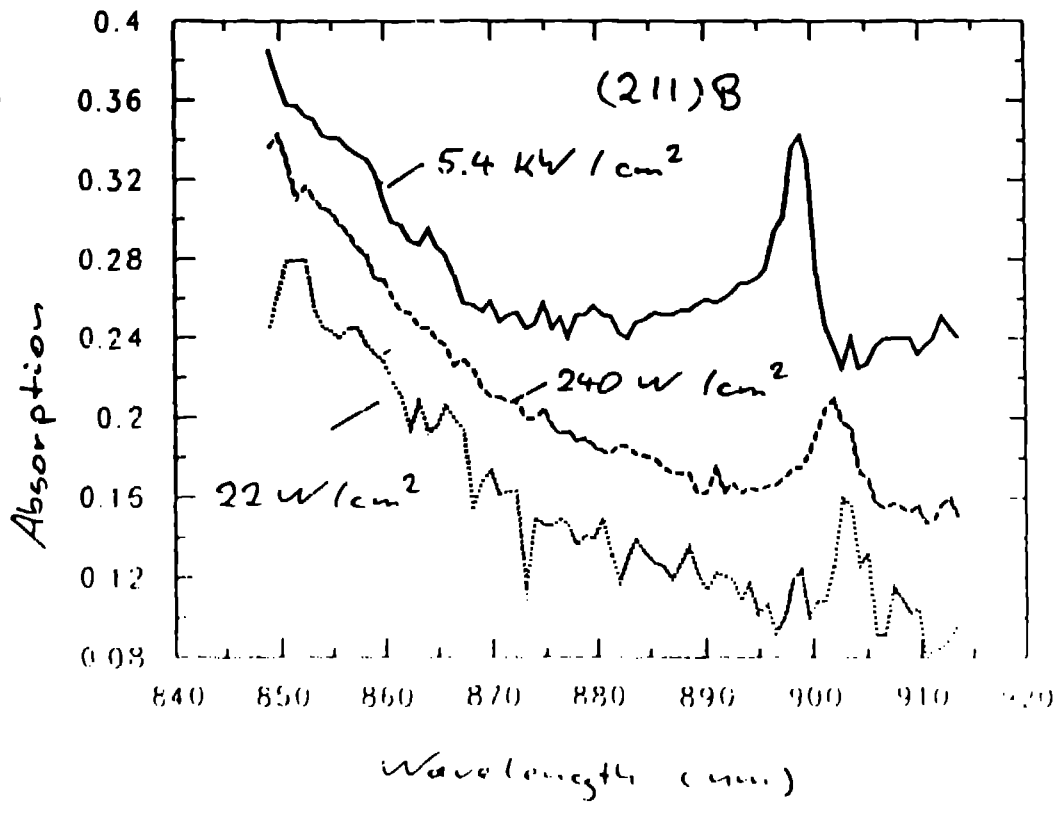
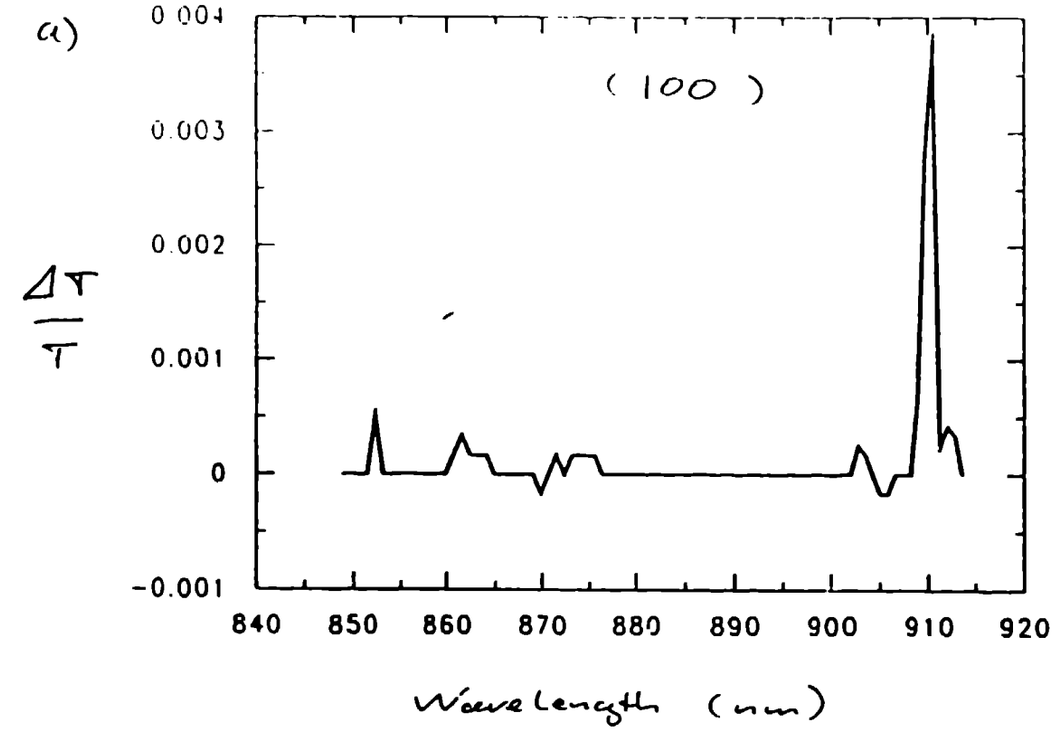

(211)B
5.4 kW/cm²
240 W/cm²
22 W/cm²
Absorption
0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
840
850
860
870
880
890
900
910
Wavelength (nm)

Fig. 7


a)
0.004
0.003
0.002
0.001
0
-0.001
ΔT/T
(100)
840
850
860
870
880
890
900
910
920
Wavelength (nm)

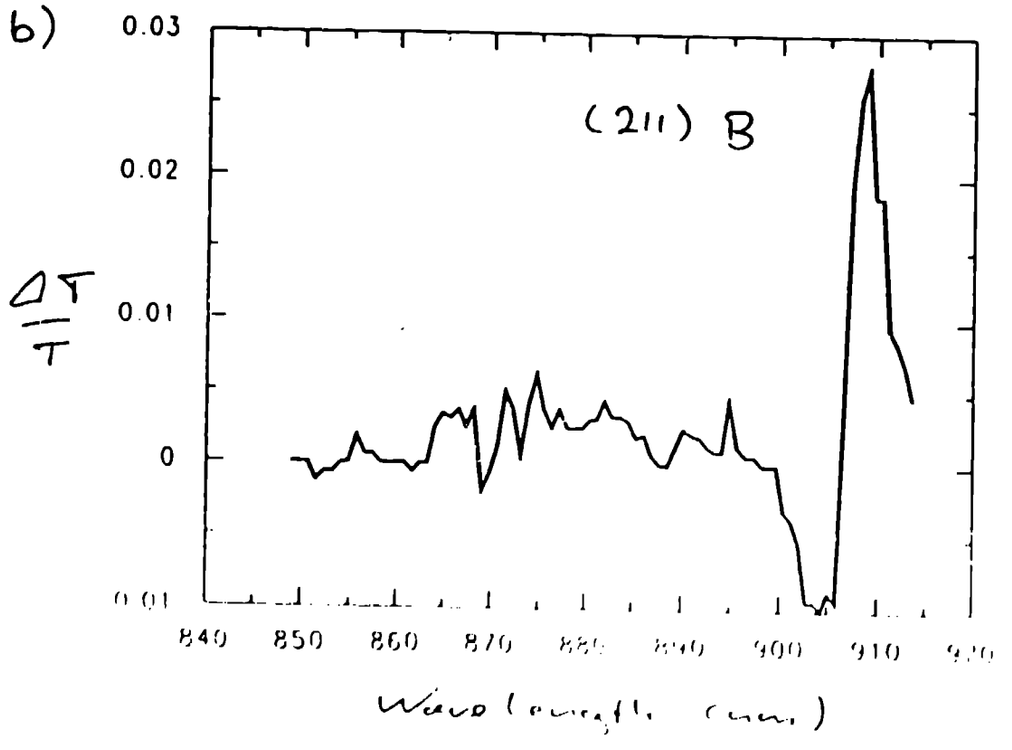

b)
0.03
0.02
0.01
0
0.01
ΔT/T
(211) B
840
850
860
870
900
910
Wavelength (nm)

Fig 3

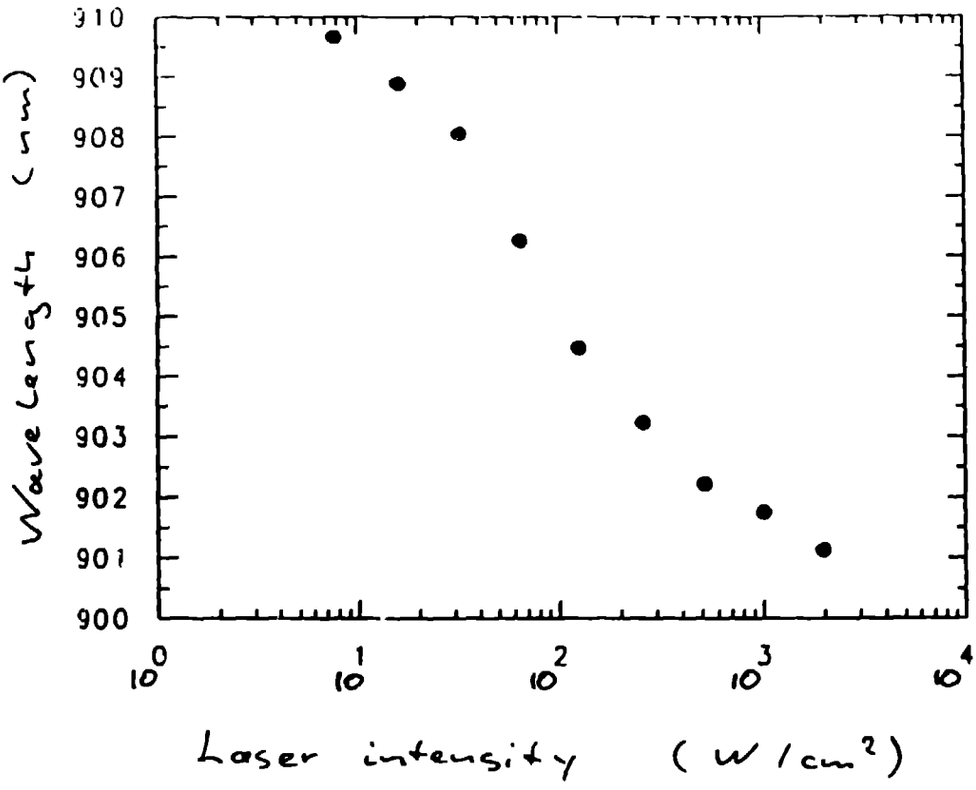

910
909
908
907
906
905
904
903
902
901
900
Wavelength (nm)
10^0
10^1
10^2
10^3
10^4
Laser intensity (W/cm²)

Fig. 4