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ABSTRACT

A description is given of a Q-switched ruby laser used for producing laser-doped contacts on semiconductors. Homogenisation of the laser beam and measurement of the output energy are discussed and some attention is given to the problems of sample reflectivity.

A brief outline of the laser-doping process is provided, together with recent experimental results and details relating to the production and analysis of the contacts. A preliminary result of defect characteristics after laser irradiation of germanium is also presented.

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CRYSTAL DEFECTS; CRYSTAL DOPING; DOPED MATERIALS; ELECTRIC CONTACTS; GERMANIUM; LASER RADIATION; Q-SWITCHING; RUBY LASERS; SEMICONDUCTOR MATERIALS; SILICON

CONTENTS

1. INTRODUCTION

The availability of high-power pulsed (Q-switched) and continuous wave lasers has led to development of a number of innovative processes which exploit the unique characteristics of these directed high-energy sources. One such process, the rapid surface layer melting and subsequent solidification of metallic and semiconductor substrates, has had numerous applications over the past three years [Materials Research Society 1981]. However, one application which has not been well studied is the use of pulsed lasers to produce contacts on semiconductors from thin surface layers. In this paper we describe a laser system with output parameters which are suited to the production of doped contacts. These parameters and their experimental measurement are presented.

The laser-doping process is discussed briefly and recent experimental observations of work on silicon and germanium are presented.

2. RUBY LASER

The laser described in this paper is an updated G and E Bradley type-350 ruby system and is on loan to the AAEC from the Physics Department of Sydney University. The system, comprising the laser head, Q-switch assembly, mirrors, capacitor bank and associated electronics, is shown schematically in Figure 1.

The ruby rod, 16 mm diameter and 165 mm long, is cut from a single crystal of aluminium oxide doped with 0.04 per cent chromium. The rod has the optic axis oriented at 90° to the rod axis to provide a plane polarised output. The rod is cooled by water at 20°C which passes around it through a quartz tube.

The flash lamp consists of a quartz envelope filled with xenon gas at a pressure of 60 kPa and fitted with sealed electrodes at each end. If necessary, the flash lamp can also be water cooled.

Two aluminium sections fit together to form a light-sealed cylinder of elliptical cross-section and make up the reflector cavity. The ruby rod and xenon flash tube are located at each focus of the cylinder ellipse. The inner surface of the cylinder is anodised and highly polished to form an efficient reflector.

Two mirrors reflect the (laser) light beam within the laser cavity. The rear mirror is a dielectric-coated quartz plate with a reflectivity of >99 per cent at the operating wavelength of 694.3 nm. The front mirror is a dielectric-coated quartz plate with a reflectivity of 30 per cent. For more detailed information on ruby lasers see Lengyel [1971].

For the high powers required to be obtained (> 100 MW), lasing must take place as a single, short duration pulse < 100 ns. This is achieved by operating the laser in the Q-switched mode [Lengyel 1971] using an Inrad capacitive electro-optic Q-switch. These electro-optic devices allow routine switching operations with times of the order of 1 ns.

2.1 Laser Output

The laser is operated in the Q-switched mode at output energies up to 6 J/cm^2 with a pulse width of approx. 30 ns. The output beam has a diameter of 16 mm and a divergence of approx. 2 mrad. Energy output as a function of energy input is shown in Figure 2a while Figure 2b shows typical output pulses.

It is known that a laser beam can have an exceptionally non-uniform intensity distribution if multi-mode laser operation is employed, yielding the shape shown in Figure 3a. Single-mode operation gives a beam with a simple Gaussian output (Figure 3b) but has a considerably smaller power output. For our experiments, the laser was always used in multi-mode operation to maximise power output.

For the laser doping and other experiments we required relatively large beam areas (> 1 cm^2) with uniform energy distribution. This idealised output can be approached [Cullis et al. 1979] by introducing the multi-mode laser beam into a silica rod which acts as a diffuser and homogeniser. Because of a delay in obtaining a silica rod, our doping measurements were made using Perspex rods in the shape shown in Figure 4. The input faces of the Perspex homogenisers were ground with 600 grade carborundum to give a flat diffuse surface. As the laser beam enters the Perspex it is strongly diffused and considerable speckle is introduced. The latter (together with any residual mode pattern) can, if allowed to propagate in the rod, produce damage in irradiated specimens. However, as the radiation propagates down the homogeniser, repeated internal reflections further diffuse the beam and speckle components are progressively eliminated. This process is enhanced by the introduction of the bend. After the bend, the rod is tapered to constrict the guide and so obtain an increased beam power density. The output end of the rod is flat and polished. However, because the beam is now diffuse, it is essential that samples to be irradiated be placed within 1 to 2 mm of the output end.

Perspex is far from an ideal material for this application and becomes irreparably damaged after relatively few laser shots. Some idea of the type of damage sustained is shown in Figure 5. To ensure success for the measurements, new rods were used after ten or so laser firings. Water-filled glass tubes, which are easily manufactured, may prove to be satisfactory alternatives to Perspex; initial testing of these has shown promise.

2.2 Measurement of Beam Uniformity

The beam uniformity at the output of these Perspex homogenisers has been checked using burn marks on heat sensitive paper and exposed photographic film. However, this method is non-linear with power density and limited in detail.

A different technique (erroneously called 'laser drive in') utilises the ability of the laser to melt, at the same instant, both a thin evaporated layer on the surface of a semiconductor and the semiconductor surface. The thin surface layer partly diffuses into the molten substrate layer and an analysis of the diffusion depths gives an indication of the beam uniformity. This analysis is done using Rutherford backscattering (RBS) which uses a 1 mm beam of 2 MeV.He^+ ions to bombard the surface under study. The He^+ ions may be scattered by collisions with the surface atoms or may channel through the surface. Observation of scattering and channelling gives information on the surface composition and crystal structure. We carried out such an experiment and used a Perspex homogeniser to laser irradiate a 10 mm diameter spot on a Ge sample onto which a thin (< 20 nm) layer of In had been evaporated. This formed a laser-doped contact and an RBS scan was made across the diameter of the contact.

Data were collected on spots 1 mm apart in both random and channelled <100> orientations. The contact area uniformity was then assessed as a function of impurity concentration and crystalline quality. The results, shown in Figure 6a, indicate that in this case the contact area was not completely uniform. The reason is not obvious but may be caused by lack of co-planarity, a 'hot spot' in the beam from the homogeniser, or a radiation damage effect. We have sometimes observed patterns on laser-doped contacts which have probably been caused by such a non-uniformity. A similar measurement, made with As implanted into Si, indicates a more uniform output (Figure 6b). The higher melting temperature required for Si may have had a smoothing effect.

2.3 Power and Energy Measurement

To ensure reproducibility of results, it is necessary to measure the output energy and the output pulse energy for each laser firing. Calorimeters of design similar to that of Jennings [1966], were used to measure the beam energy entering and leaving the Perspex homogeniser for a range of capacitor bank voltages. Typical results are shown in Figure 7 for outputs from the laser before and after passing through the Perspex homogenisers. The energy loss through the Perspex homogeniser is approx. 50 per cent.

Pulse widths were measured using a beam monitor of design similar to that of Falconer et al. [1974], which relies on a fast p-i-n diode to measure the laser pulse. From Figure 2b it is seen that the Q-switched laser pulse has a width of approx. 30 ns.

Conventionally, laser energies or energy densities incident on the sample are quoted. However, more meaningful would be a measure of the absorbed energy. This can be calculated if the reflectivity of the surface involved is known. The reflectivity is, in general, a function not only of the temperature but also of the nature of the surface.

We used calorimeters to measure the amount of energy absorbed by samples of crystalline Ge having different surface finishes. These finishes were attained by varying the amount of chemical etching performed on a sample which initially had a 600 grade SiC finish. The level of laser energy to be used was chosen such that the surface did not melt. From the results presented in Figure 8, it can be seen that after two minutes' etching the absorption became constant and the reflectivity saturated at approx. 0.36 units. This value agrees well with that shown by Stuke [1970]. It is interesting to note that after two minutes, the sample surface appeared far from specular. We intend to repeat these measurements with Si and to investigate surfaces having different thicknesses of amorphous Si and Ge.

3. LASER-DOPED B CONTACTS

The laser-doping process [Lawson 1981] depends on the simultaneous melting of a thin layer of dopant and the surface of the substrate. The dopant layer can be formed by evaporation, spin-on coating, gas cell, etc. A contact is produced by using a laser pulse to melt both the dopant layer and the substrate surface, then to mix semiconductor and dopant. As the molten layer cools, the crystal regrows epitaxially and some of the dopant is incorporated in the crystal in an electrically-active form.

We have used the spin-on technique to produce laser-doped B contacts. The source of B was a boro-silicate spin-on dopant* normally used for furnace diffusion of Si (for device production). We spun the dopant onto the surface of two 27 mm diameter slices of 300 Ω cm n-Si. After drying them, we used the homogenised laser beam (3.7 J cm^{-2}) to irradiate them and so form the pattern shown in Table 1. This pattern was used to measure sheet resistivity and Hall effects (SRH) and so evaluate the quality of the contacts. The results are presented in Table 1, along with similar results from Narayan et al. [1978] who made contacts on Si by laser irradiation of B layers produced by e-beam evaporation. Our contacts show slightly superior effective mobilities but poorer sheet resistivities and carrier concentrations.

4. DEEP LEVEL TRANSIENT SPECTROSCOPY MEASUREMENT OF DEFECTS IN Ge

It is known that the rapid melting and cooling achieved by laser irradiation can be beneficial in device manufacture. For example, the epitaxial layer which regrows after laser melting is free from extended crystallographic defects [White et al. 1979]. Such defects as dislocation loops, for example, may start to propagate from the substrate. As the growth rate of these defects is much less than that of the retreating melt-solid interface, the laser-melted region is left relatively free of them. However, electrically-active point defects remain which can trap carriers and reduce lifetimes. For device manufacture it would be necessary to remove these point defects, perhaps by thermal annealing or hydrogen passivation [Benton et al. 1980]. A convenient technique to characterise such defects, deep level

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* Boro-silicate 5257; Merck, Germany

transient spectroscopy (DLTS) has been described by Lang [1974]. In a preliminary experiment we used DLTS to look for such defects in Ge after laser irradiation.

A sample of n-Ge was irradiated with the Q-switched ruby laser and then prepared for DLTS measurement. The result of this preliminary measurement is shown in Figure 9 and gives a clear indication that these defects are present in the laser-irradiated region of the Ge. The defect concentration N_T was measured as 1.1×10^{12} cm^{-3} and the defect level was -0.18 eV.

5. CONCLUSIONS

The Q-switched ruby laser system, when coupled to a suitable diffuser-homogeniser, has proved satisfactory in producing doped contacts on both Si and Ge. The use of spin-on dopants which is simple and offers promise for future development, should be continued. More work is required with B dopants if improvements to sheet resistance and carrier concentration are to be effected. The role of the deposited layer before laser irradiation is obviously important and needs further study.

Perspex homogenisers, although successfully used for these experiments, take too much effort in manufacture compared to their extremely short lifetime. All future work in this area will be conducted using fused silica.

Little work has been done on the reflectivity of pulsed laser beams from the materials being irradiated. This is an area of research which, although important, to date has received little attention and should, therefore, be examined.

Work will continue with DLTS measurements of laser-melted regions. Our experiments show clearly that all future work in this and related fields involves multi-disciplinary techniques to an extent we did not anticipate.

6. ACKNOWLEDGEMENTS

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Narayan, J., Young, R.T. and Wood, R.F. [1978] - Appl. Phys. Lett., 33(4)338.

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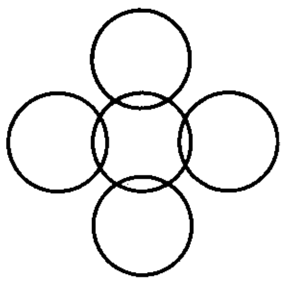
TABLE 1

COMPARISON OF SRH MEASUREMENTS ON LASER-DOPED B CONTACTS

Laser Spot Pattern	Sample No.	Current (mA)	Sheet Resistivity (Ω/□)	Impurity Conc. (cm^{-2})	Effective Mobility $cm^2\ V^{-1}\ s^{-1}$
	n-Si-300-1	1.0	472.5	2.50×10^{14}	52.9
		0.1	470.5	2.50×10^{14}	53.1
	n-Si-300-2	1.0	437.6	2.61×10^{14}	54.7
		0.1	438.6	2.59×10^{14}	55.0
Results from Narayan et al. 1978	BD-10		80.0	2.1×10^{15}	40
	BD-11		23.8	8.62×10^{15}	31
	BD-12		22.0	9.37×10^{15}	30
	BD-13		32.0	6.10×10^{15}	33
	BD-25		8.2	3.13×10^{16}	24

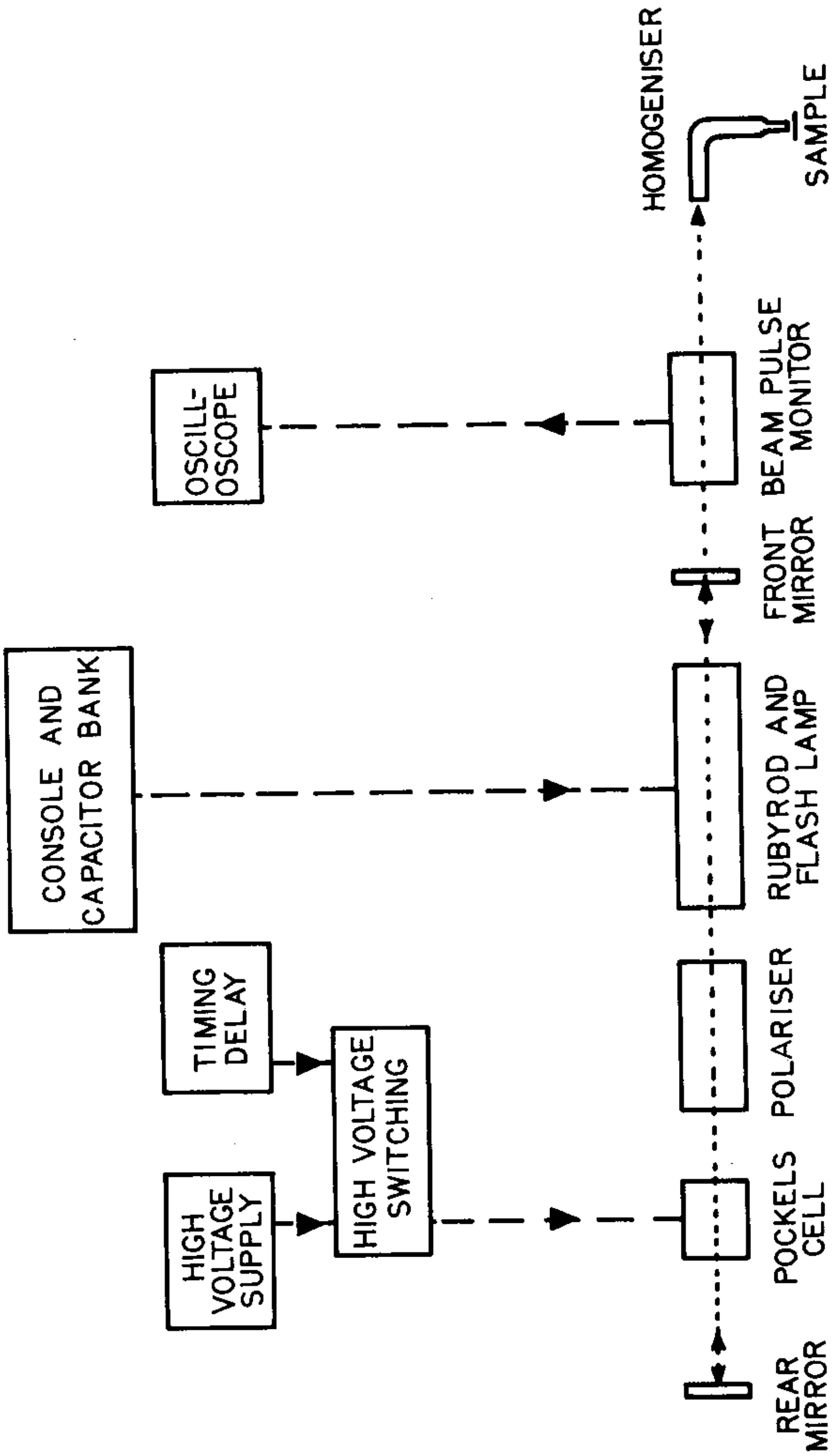


FIGURE 1. SCHEMATIC DIAGRAM OF RUBY LASER SYSTEM

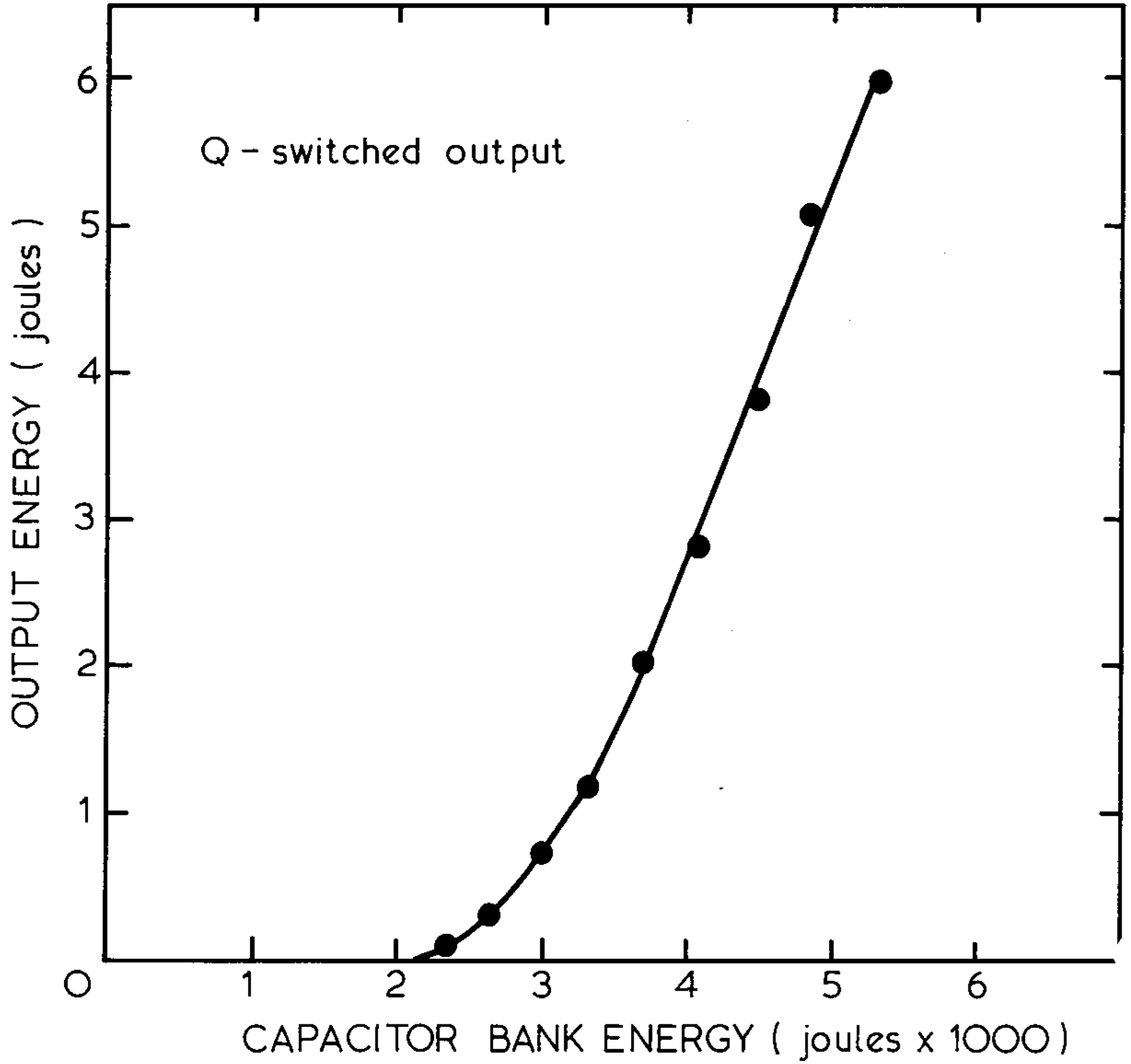


FIGURE 2a. ENERGY OUTPUT AS A FUNCTION OF ENERGY INPUT

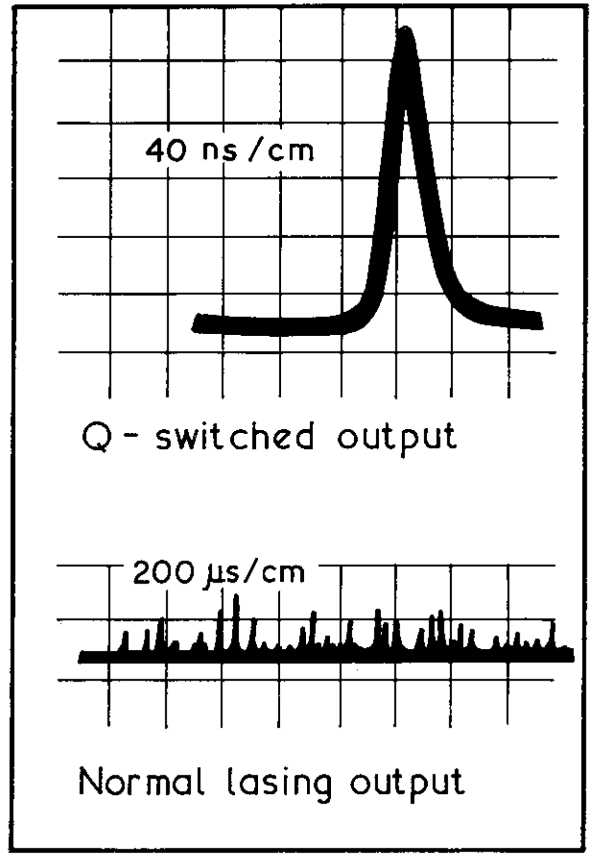


FIGURE 2b. RUBY LASER OUTPUT PULSE SHAPES

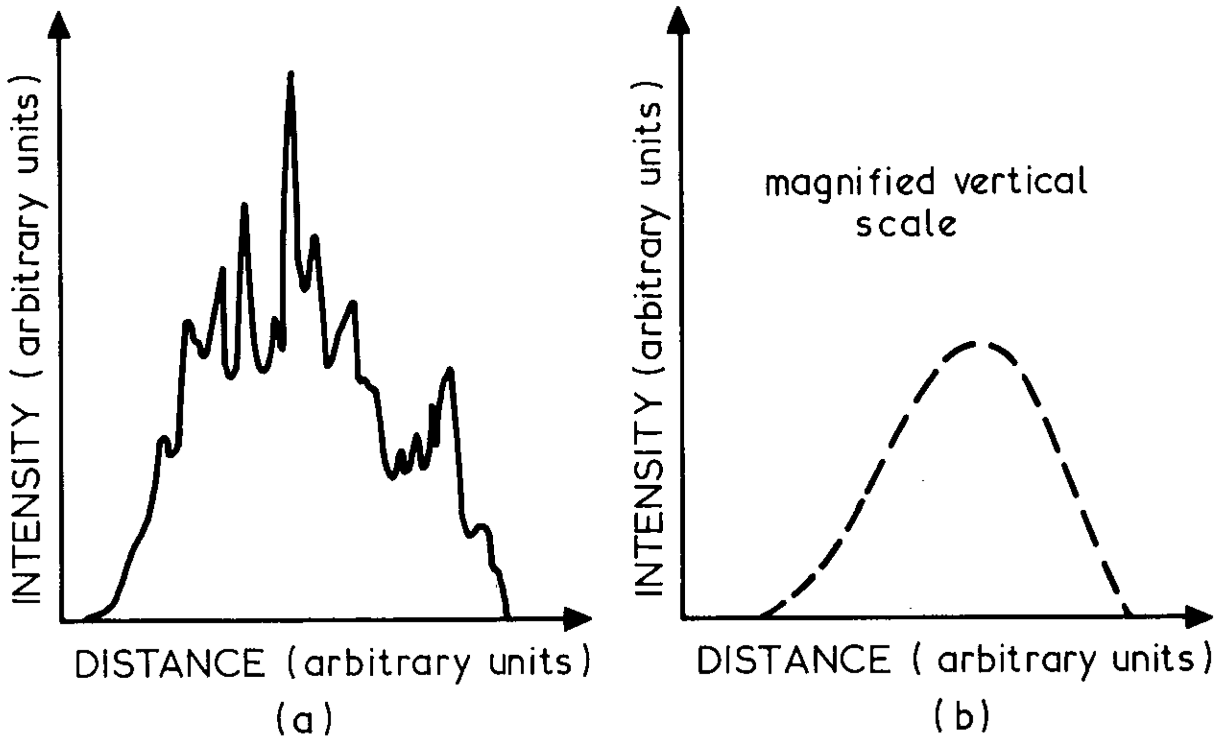


FIGURE 3. SCHEMATIC OF EXPECTED INTENSITY PROFILES ACROSS THE DIAMETERS OF MULTI-MODE SPOT (a) AND SINGLE-MODE SPOT (b)

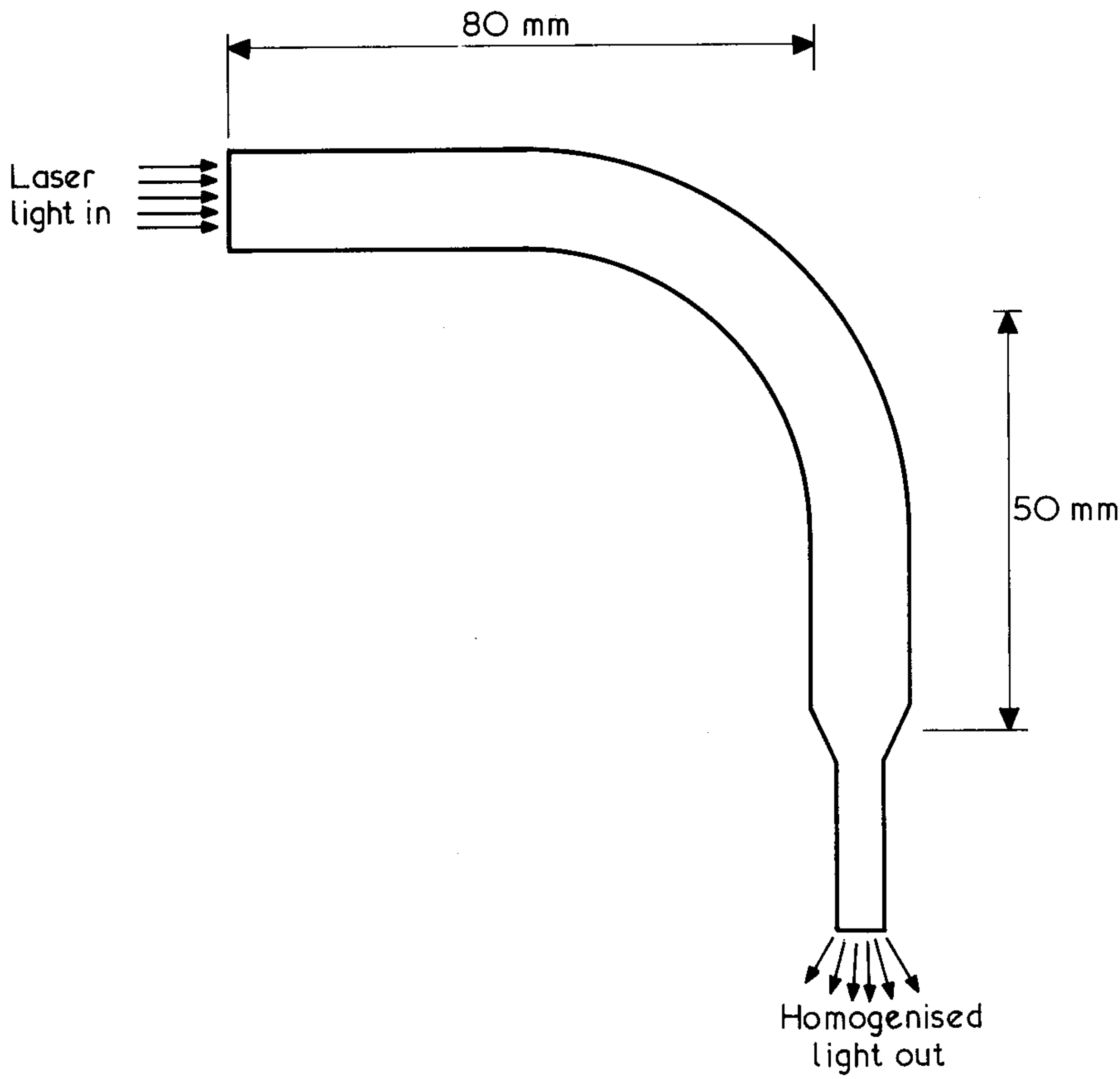


FIGURE 4. PERSPEX HOMOGENISER

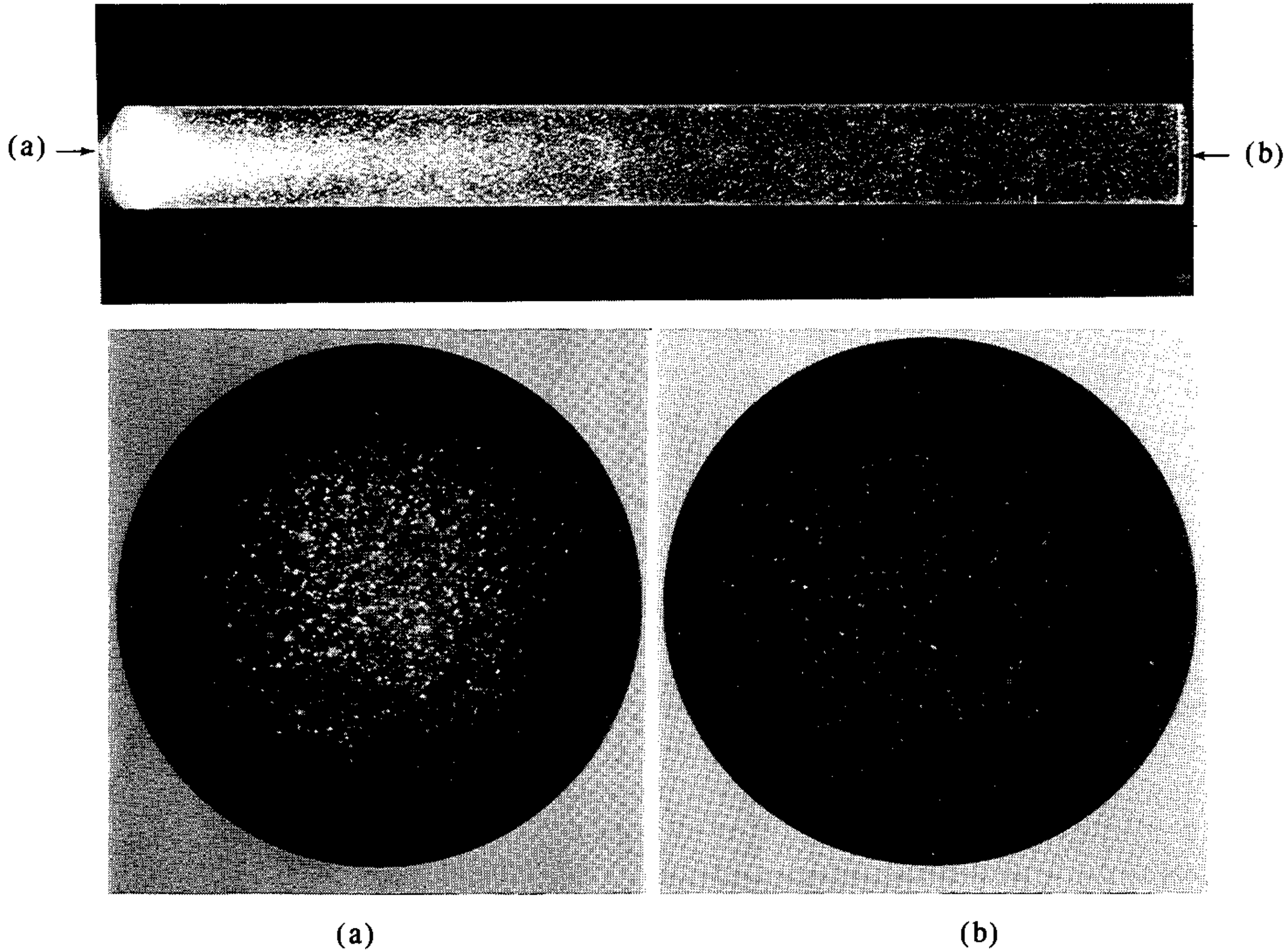


FIGURE 5. DAMAGE SUSTAINED BY PERSPEX AFTER MULTIPLE LASER SHOTS

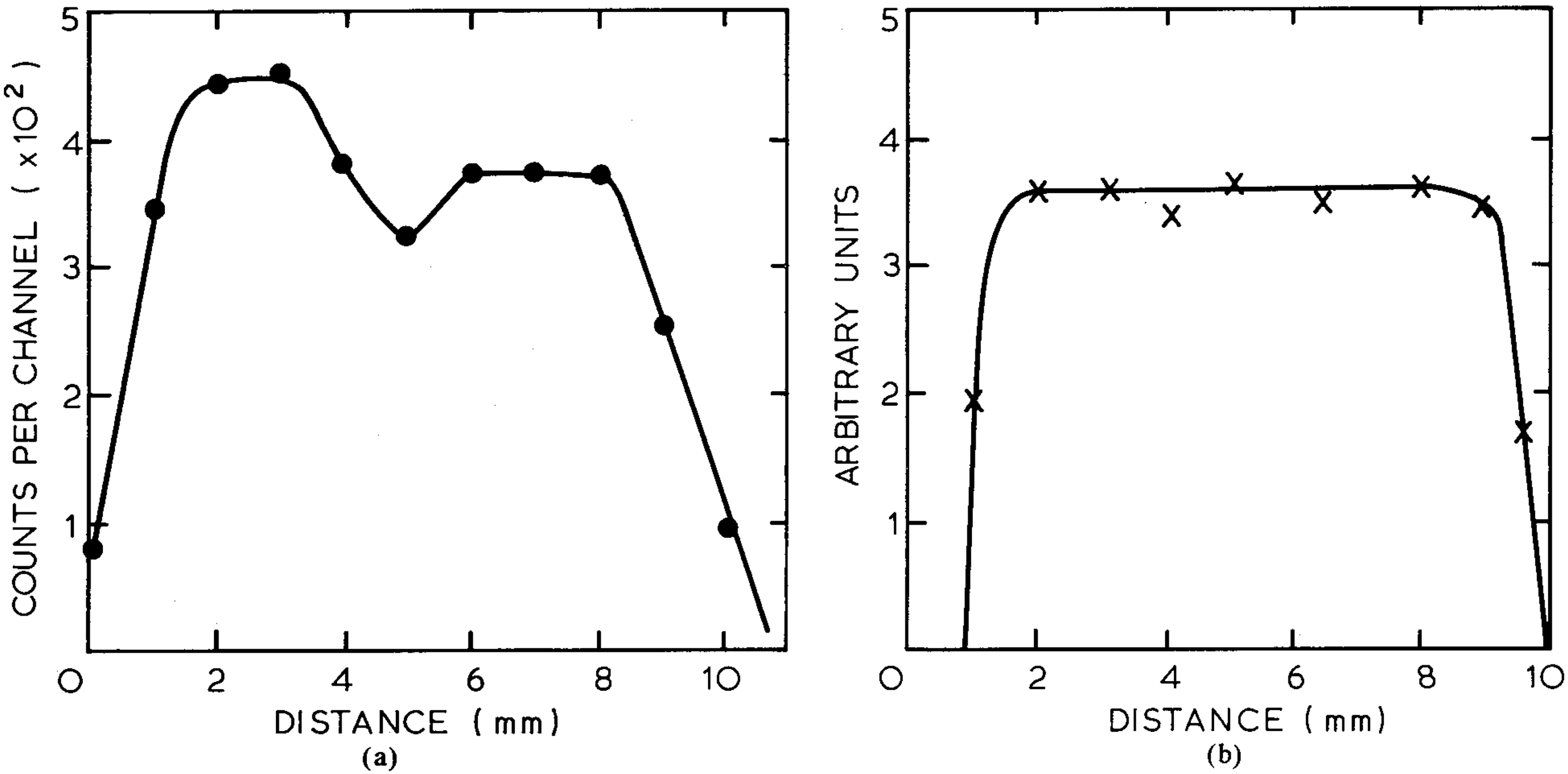


FIGURE 6. RBS SCANS ACROSS BEAM SPOTS

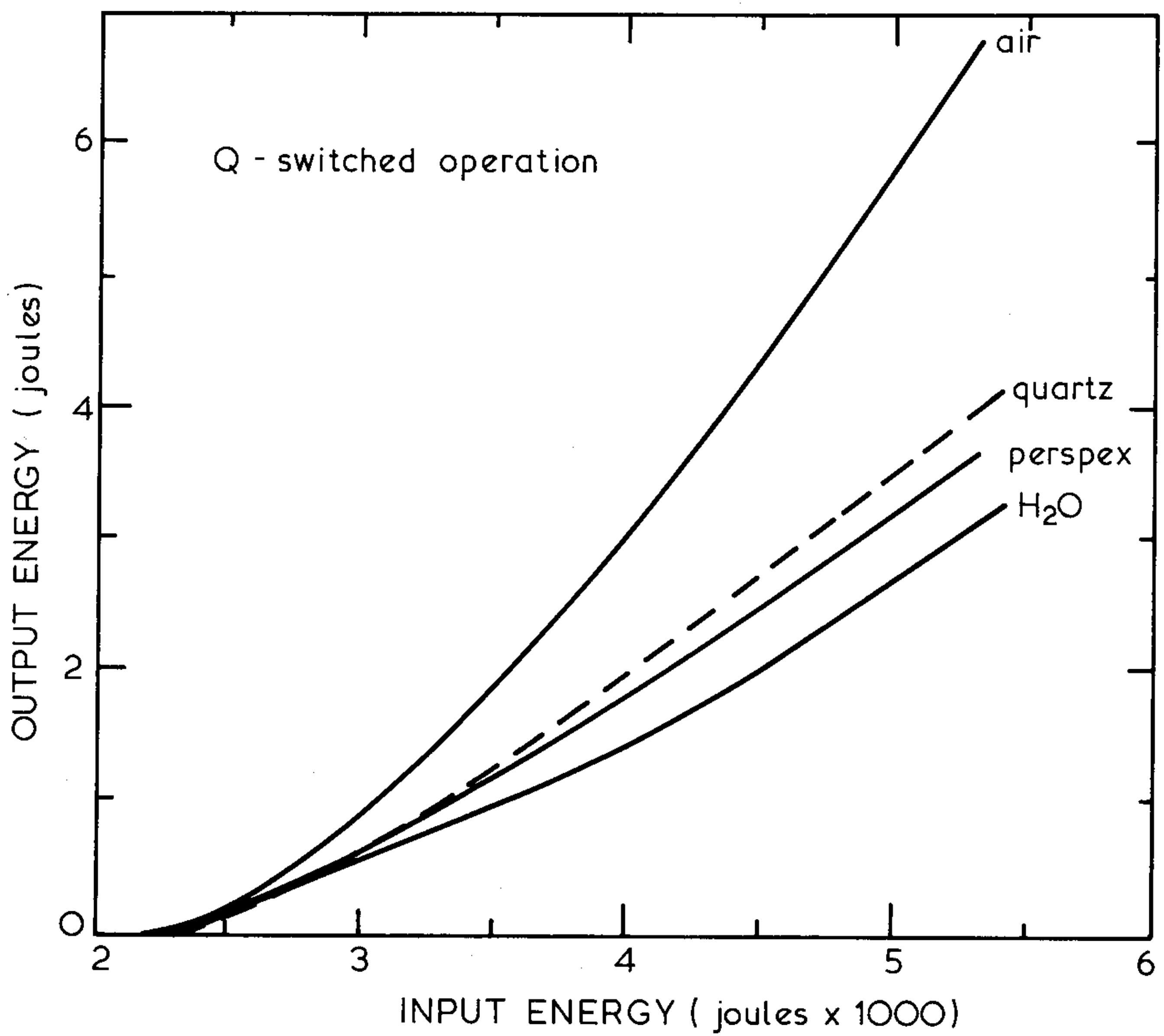


FIGURE 7. COMPARISON OF ENERGY OUTPUTS

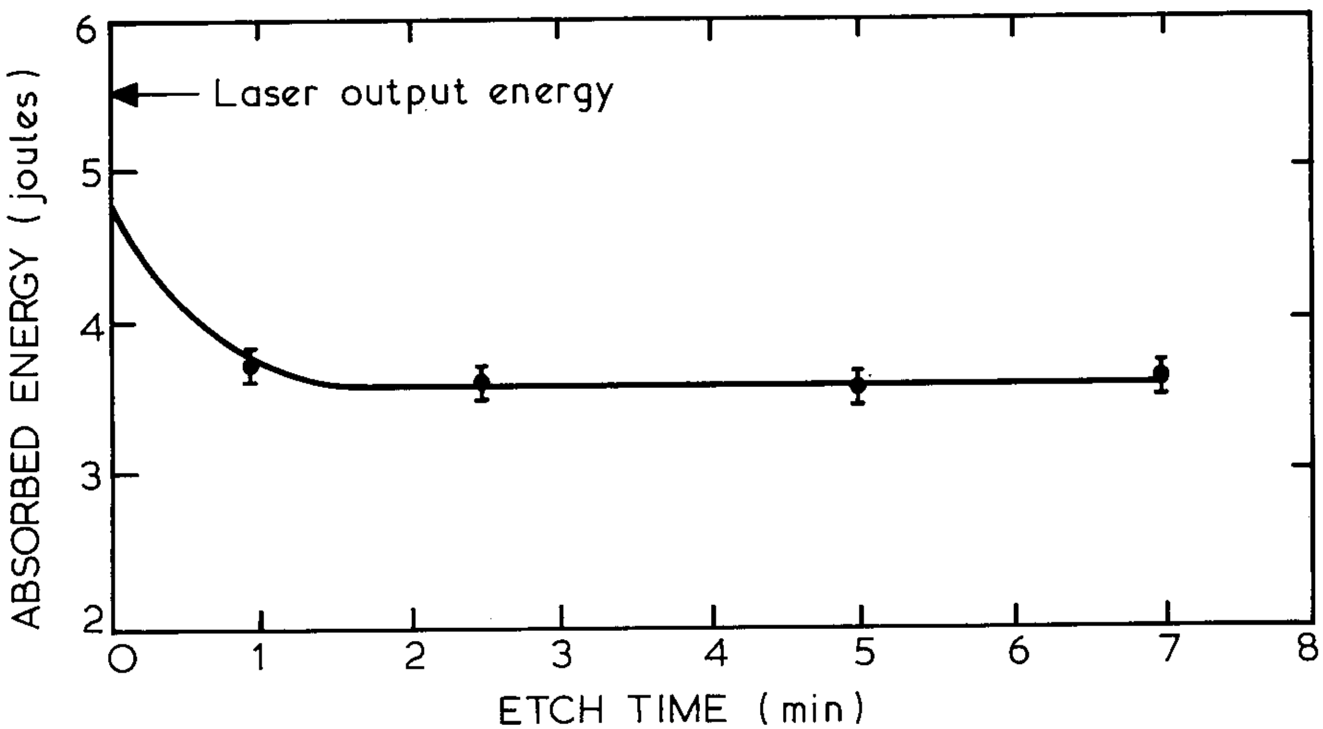


FIGURE 8. RELATIONSHIP BETWEEN ABSORBED ENERGY AND ETCHING TIME

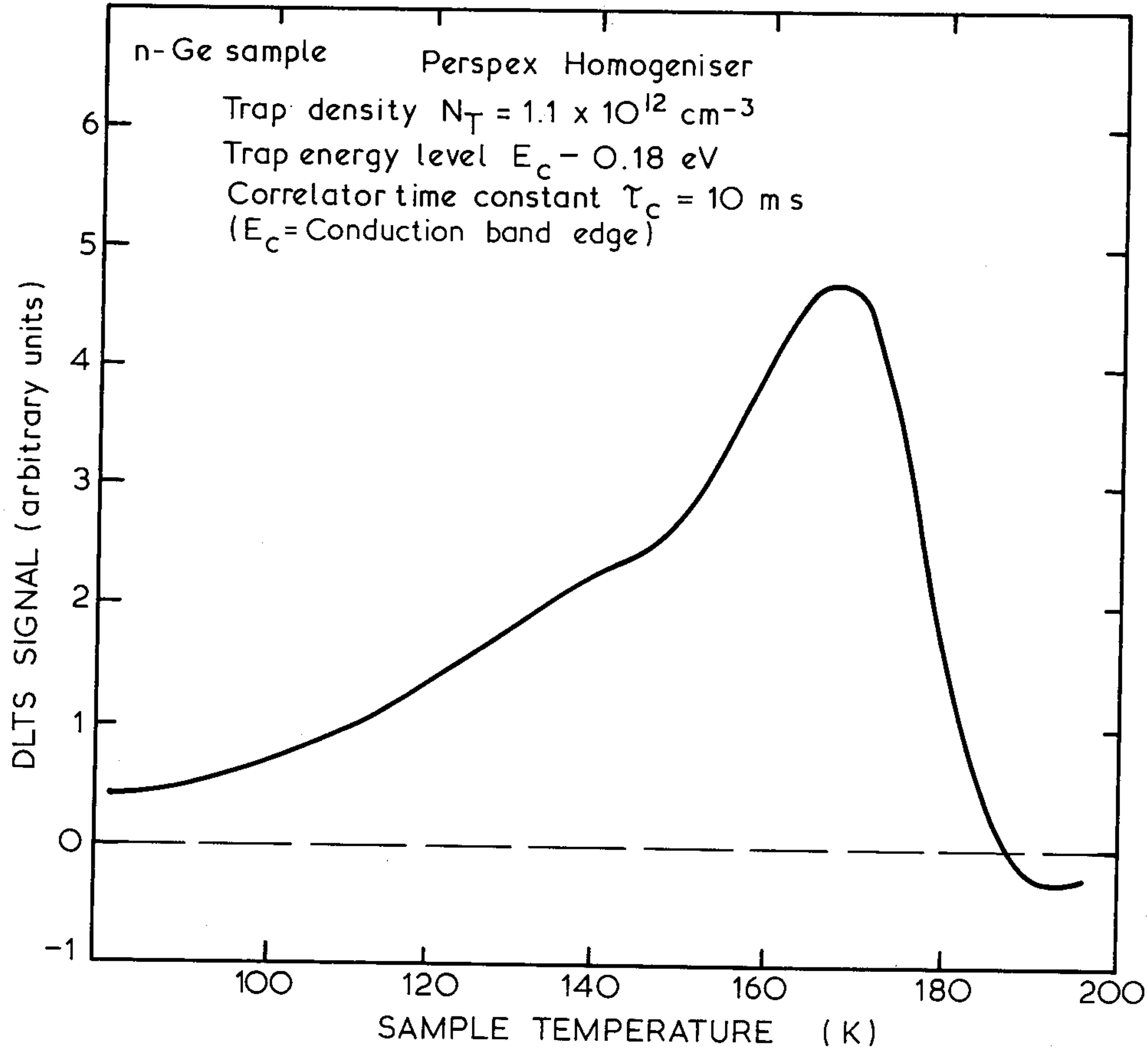


FIGURE 9. DLTS SPECTRUM FROM n-Ge SAMPLE