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COMMENTS ON THE MECHANISMS OPERATING IN LASER ANNEALING

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In the discussion on the various mechanisms acting in laser annealing we think useful to draw attention on some of our old works which, for convenience, are reproduced here in figure 1.

**Figure 1** refers to some research on laser annealing of polycrystalline silicon /1,2/. In the experiment a layer of 4000 Å of polycrystalline silicon was obtained on top of a single-crystal Si material. The following facts were found:

1) The power density needed to obtain a good single crystal was about 70 MW/cm², against the 40-50 MW/cm² needed for an equal thickness of amorphous material. At 70 MW/cm² the surface was slightly damaged, a fact which seems to be indicative that some melting has occurred /2,3/.  

2) The transition could be obtained also by using several separate shots of 50 MW/cm². In this case with a single shot the transition already occurred but the resulting material showed a very high residual disorder (Fig.1a curve 1). With second shot of equal power density, on the same region on which the first shot was given, the damage was reduced and it decreased even more when three or four shots were used /2/. In the backscattering curves (Fig.1a curves 1 to 3), a shoulder is always present at the interface single crystal-initially polycrystalline layer, indicating that this interface is in any case the more disordered region. Similar results have also been obtained by K. Baither et al. /4/ who have found that under separated pulsing with a Q-switched ruby laser operated below the threshold for melting, amorphous Si becomes a highly disordered crystal which reorders under repeated pulses.

3) A much better final result is
obtained by using a time shaped pulse train (s. curve 4 in Fig. 1a) /2/, /3/, /5/.
If the previous results are to be explained on the basis of the melting theory /6/, /8/, the simplest explanation of the superposed separate shots experiment is one which makes recourse to the observation that the spatial distribution of intensity in the laser shot is usually not very uniform and changes randomly from one shot to the other. It is very likely that some regions in the spot are characterized by a power density much higher than the average value of 50 mW/cm², such that they are able to melt the layer all down to the substrate. Under repeated shots the random distribution of hot points makes the full transition possible.
In the same melting hypothesis the experiment of the time shaped pulse train is interpreted as a gentle fusion of the material which lasts for a much longer time and prevents the surface to attain a too high temperature value.
The basic idea is here very simple and can be illustrated as follows.

If a train of pulses of decreasing power is sent over the surface of some material, the consequent temperature increase can be driven gently, and if melting occurs, the melt front can be made to progress inside the material at a slow velocity while the surface temperature can be prevented from attaining large values. Of course similar effects can be obtained using other tailored pulses as for example a saw-tooth shaped pulse; the time shaped pulse train is however easier to be produced.

The used train is shown in Fig. 2a. A simple calculation shows how the surface temperature can be kept nearly constant by properly shaping the pulses (s. Fig. 2b and c); where the calculation has been performed in a case in which surface temperature is always lower than the melting temperature of Si /7/.
Evidence of better recrystallization of the surface irradiated with this kind of pulses has been presented in references /2/ /3/ and /5/; and the residual disorder was shown to be very low; even smaller than

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Fig. 2. a) The actually used pulse train b) The pulse train used in the calculation c) The consequent temperature increase at the surface of an a-Si sample, if a power density as shown in b) is used.
the one after 4 shots of 50 mW/cm² each.

In some respect similar considerations can be made in a completely different experiment in which a pulse from a free-generation ruby laser is used to make polycrystalline an initially amorphous layer. This was one of our first experiments /8/ and we calculated that the average maximum temperature increase at the surface never exceeded 150°C. Thermal annealing after the laser irradiation showed that under shots of increasing power density an amorphous layer of decreasing thickness was present under the polycrystalline material between the single crystal and the polycrystal (Fig.1b). Again this experiment shows that the polycrystalline material nucleates in the amorphous material and not from the single crystal-amorphous interface.

Moreover if several separate equal laser shots are superposed, the polycrystalline transition becomes more and more evident. An analysis of our results leads us to conclude that under repeated shots the more important phenomenon occurring is the increasing of the number of single small crystals, rather than of their size.

The conclusion from these observation is that in this case it is hard to define a threshold, and it is better to speak of a minimum power density necessary to obtain detectable results. An explanation of the transition can be also afforded in this case, by making recourse to the spatial inhomogeneity of the laser spot. It is quite possible that in each shot there are hot spots randomly distributed in space which can act as nucleation centers.

Under repetitive shots these nucleation centers increase in number due to the random distribution of the hot spots, and the produced crystals are not increasing in dimensions.

An increase in dimensions can only occur if the power density of the single shot is increased.

Finally we wish to report on some new results recently found on the essential role of the ionization produced by the laser /9/. The effects of ionization on annealing of defects in semiconductors has been also reviewed at this workshop /10/ and recently laser annealing of disordered but not amorphous semiconductors, has been presented /11/.

We have studied the effect of a continuous Ar laser (λ = 0.545 µm) on γ-irradiated germanium /12/.

The used samples were doped with P. Under γ-irradiation a level at energy $E_C$ = 0.2 eV is developed whose isochronal recovery curve is shown in figure 3./13/.

![Fig.3.- Isochronal recovery curve of the defect $E_C$ 0.2 eV in Ge doped with P-a is the unannealed defect fraction.](image)

The maximum temperature attained by the samples under the laser irradiation was monitored with a thermocouple. The preliminary results show that complete recovery of electrical properties (carrier concentration, conductivity and mobility) is obtained independently of the maximum temperature reached by the sample after about 20 minutes of laser irradiation, and in particular they are also recovered at a temperature below 35°C. These results seem to show that ionization is the predominant annealing mechanism in this case. A tentative explanation can be found in a change of charge state of defects under the ionization produced by the laser light.

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/11/s.papers at the Int.Conf.on Rad.Phys.of Semi. and Related Materials, sept. 13-19, 1979 Tbilisi, USSR.

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