

FIG. 4

## CONCLUSIONS

1. For a number of pure metals (Al, V, Ni, and Cu) the dose dependence of the degree of radiation hardening has a tendency to saturate (at damage doses in the range  $10^{-4}$ - $10^{-2}$  displacements per atom).

2. The temperature dependence of radiation hardening in copper has been measured at a dose corresponding to saturation of the hardening effect. A reduction in the radiation hardening is observed at temperatures above 200°C, in agreement with the temperature variation in the concentration and sizes of defect clusters<sup>9</sup> and, apparently, is explained by a growth in the mobility of vacancies.

3. Electron microscope studies showed that during irradiation by heavy ions, as with other

particles (neutrons and light ions), radiation hardening is caused by clusters of radiation defects with dimensions of up to 5 nm.

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# On the domain of application of fast *n*-InSb submillimeter detectors cooled to $T=77$ K

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Powerful, pulsed, tunable, optically pumped lasers, lasing in the range 30-2000  $\mu$ m and having a pulse duration of  $10^{-7}$ - $10^{-9}$  sec and power up to 10 MW (see, e.g., Ref. 1), are now used for the solution of many problems (plasma diagnostics, nonlinear spectroscopy of solids, etc.). To detect such radiation, quick-response *n*-InSb detectors cooled to  $T = 77$  K are, in particular, employed.<sup>2</sup> Their principle of operation is based on intraband photoconduction, observed in *n*-InSb in Ref. 3. The speed of this effect is determined by the intraband energy relaxation time, which amounts to  $\sim 10^{-10}$ - $10^{-11}$  sec. When powerful, optically pumped, pulsed lasers appeared these detectors, together with detectors based on the drag effect and heating photoconductivity in Ge,<sup>4,5</sup> were employed for recording short laser pulses, both with low intensity and intensity up to 1 MW/cm<sup>2</sup>.

On the other hand, it was recently found that when *n*-InSb is excited at  $T = 77$  K by quite strong submillimeter laser radiation, impact photoionization

occurs.<sup>6</sup> This process gives rise to nonequilibrium carriers in the semiconductor and, correspondingly, concentration photoconductivity together with intraband photoconductivity. The amplitude of the concentration photoconductivity signal grows exponentially as the intensity of the light *I* is increased, and for sufficiently large *I* it exceeds the amplitude of the intraband photoconductivity signal. The kinetics of the concentration photoconductivity signal is governed by the lifetime  $\tau$  of the nonequilibrium carriers, which amounts to  $\sim 10^{-6}$ - $10^{-7}$  s in *n*-InSb at  $T = 77$  K. Since the duration of the laser pulse  $\tau_p$  is, as a rule, much shorter than the lifetime  $\tau$ , the kinetics of the observed photoconductivity signal with strong light intensities does not reflect the kinetics of the laser pulse.

In this connection we performed experiments in order to determine the domain of applicability of quick-response *n*-InSb detectors operating at  $T = 77$  K. The experiments were performed using for the source of radiation a powerful, optically

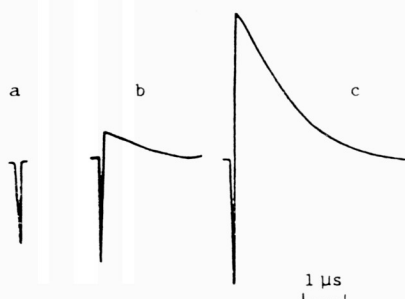


FIG. 1. Oscilloscope traces of the photoconductivity signal, obtained on an n-InSb sample ( $n = 9.3 \cdot 10^{12} \text{ cm}^{-3}$ ) at  $T = 77 \text{ K}$  under excitation by radiation with  $\lambda = 90.55 \text{ } \mu\text{m}$  for  $I = 10$  (a), 20 (b), and  $60 \text{ kW/cm}^2$  (c).

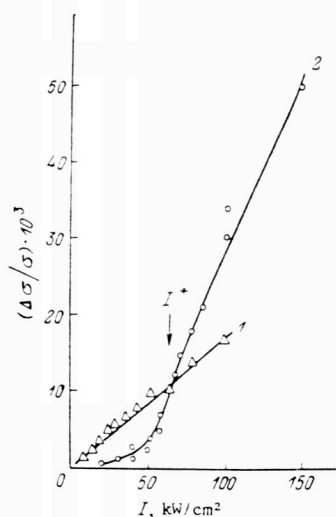


FIG. 2.  $(\Delta\sigma/\sigma)_1$  (1) and  $(\Delta\sigma/\sigma)_2$  (2) versus the intensity of radiation with  $\lambda = 90.55 \text{ } \mu\text{m}$ .

pumped, pulsed, tunable  $\text{NH}_3$  and  $\text{D}_2\text{O}$  lasers.<sup>7</sup> Lasing was achieved at wavelengths of 90.55, 140, and  $385 \text{ } \mu\text{m}$  with a pulse duration of 40-100 nsec. The dependence of the photoconductivity of n-InSb samples at  $T = 77 \text{ K}$  was studied in a wide range of concentrations.

As an example we shall examine the photoconductivity of n-InSb with  $n = 9.3 \cdot 10^{12} \text{ cm}^{-3}$  excited by light with  $\lambda = 90.55 \text{ } \mu\text{m}$  ( $\tau_p = 40 \text{ nsec}$ ).<sup>1)</sup> Figure 1 shows the characteristic oscillograms of the photoconductivity signal, obtained with different light intensities. One can see that for relatively low  $I$  (up to  $10 \text{ kW/cm}^2$ ) the form of the signal is identical to that of the laser pulse (Fig. 1a); increasing the intensity leads to the appearance of a "slow" component in the resultant photoconductivity signal (Fig. 1b), and when  $I$  is increased further the slow component makes the main contribution (Fig. 1c). The kinetics of the "slow" component corresponds to the lifetime of nonequilibrium carriers. Figure 2 shows the "fast" component of the signal corresponding to intraband photoconductivity and the "slow" component due to the production of nonequilibrium carriers as a result of impact photoionization as functions of the intensity of the radiation. One can see that the intraband photoconductivity  $(\Delta\sigma/\sigma)_1$  depends linearly on the intensity of the light (Fig. 2, curve 1), while the concentration photoconductivity  $(\Delta\sigma/\sigma)_2$  increases ex-

ponentially with  $I$  (curve 2, Fig. 2). As a result, for  $I > I^* = 60 \text{ kW/cm}^2$  (here  $I^*$  is the characteristic intensity for which  $(\Delta\sigma/\sigma)_1 = (\Delta\sigma/\sigma)_2$ ) the resultant photoconductivity is now determined by the interband generation of nonequilibrium carriers owing to impact photoionization. Thus for  $I \geq I^*$  the detectors under study strongly distort the amplitude and shape of the recorded laser pulse.

We shall now examine the spectral dependences of the concentrational and intraband photoconductivities. The photoconductivity associated with impact ionization, whose magnitude is practically equal to the relative concentration of nonequilibrium carriers  $\Delta n/n$ , has the following dependence on the wavelength  $\lambda$  (Ref. 6):

$$\left(\frac{\Delta n}{n}\right)_2 \approx \frac{\Delta n}{n} = A \exp\left(-\frac{I_0}{I}\right), \quad I_0 \sim \lambda^{-2}. \quad (1)$$

Here  $A$  is a constant that is virtually independent of  $I$ ;  $I_0$  is the characteristic intensity. One can see from (1) that as  $\lambda$  is increased the process of impact ionization is greatly facilitated and the value of  $(\Delta\sigma/\sigma)_2$  increases. The intraband photoconductivity  $(\Delta\sigma/\sigma)_1$  in the wavelength range  $300\text{-}1000 \text{ } \mu\text{m}$  also increases as  $\lambda$  increases:  $(\Delta\sigma/\sigma)_1 \sim \lambda^4$ . Our studies, performed at wavelengths of 90.55, 140, and  $385 \text{ } \mu\text{m}$ , showed that as  $\lambda$  is increased from  $\lambda = 90.55$  to  $\lambda = 140 \text{ } \mu\text{m}$  the component  $(\Delta\sigma/\sigma)_1$  changes sign and then grows rapidly as  $\lambda$  increases, which is consistent with the results of Ref. 2. To determine the value of  $I^*$  for relatively high values of  $\lambda$  the dependences of  $(\Delta\sigma/\sigma)_1$  and  $(\Delta\sigma/\sigma)_2$  on the intensity of  $385 \text{ } \mu\text{m}$  radiation ( $\tau_p = 50 \text{ nsec}$ ) were studied. It was established that under these conditions  $I^*$  is of the order of  $10 \text{ kW/cm}^2$ . Thus the lowering of the threshold for impact ionization as the wavelength is increased compensates the increase in  $(\Delta\sigma/\sigma)_1$ , and the upper limit of the dynamic range of the detectors does not increase as  $\lambda$  is increased.

In conclusion we note that the values of  $I^*$  presented in this paper are, generally speaking, approximate, since  $(\Delta\sigma/\sigma)_2$  depends on the concrete form of the recorded laser pulse. This is because for  $\tau_p < \tau$  (as a rule this inequality always holds) nonequilibrium carriers actually accumulate in the conduction band over the time of the laser pulse. Then in the simplest case of a triangular pulse the amplitude of  $(\Delta\sigma/\sigma)_2$  is proportional to  $\tau_p$ , while  $(\Delta\sigma/\sigma)_1$  does not depend on the duration of the laser pulse. Thus the values of  $I^*$  presented are valid only for laser radiation with  $\tau_p \sim 50 \text{ nsec}$ . For pulses of longer or shorter duration  $I^*$  decreases or increases, respectively.

It follows from the results presented here that the appearance of impact photoionization in semiconductors creates definite difficulties in using quick-response n-InSb detectors cooled to  $T = 77 \text{ K}$  for recording powerful submillimeter range light pulses. At the same time, when the intensity of the radiation to be detected is sufficiently weak these detectors can certainly be used.

<sup>1)</sup> In practice detectors consisting of high-resistance n-InSb ( $n \sim 10^{13} \text{ cm}^{-3}$ ) are employed,<sup>2</sup> so that in what follows the results obtained on samples with  $n \sim 10^{13} \text{ cm}^{-3}$  are presented. For other concentrations the results are qualitatively the same.

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