Microwave resonance of delayed photoconductivity in $Pb_{1-x}Sn_xTe(In)$

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A resonant increase has been observed in the photoconductivity of $Pb_{1-x}Sn_xTe(In)$ alloys during microwave pumping. The effect stems from electrons localized in metastable impurity states near the bottom of the conduction band.

In this letter we are reporting the discovery of a new effect: a resonance of the delayed photoconductivity in $Pb_{1-x}Sn_xTe(In)$ induced by a microwave signal.

The test sample was an alloy with a tin content $x = 0.25$, in which the Fermi level stabilized in the band gap, ~ 25 meV below the bottom of the conduction band.[1] The dark density of free electrons in the material did not exceed 10^6 cm^{-3} at liquid-helium temperature. Infrared illumination of constant intensity caused the conductivity of this alloy to increase linearly over time. When the light was turned off, a long-term relaxation of the photoconductivity was observed. The time scale of the relaxation was greater than 10^4 s at $T = 4.2$ K (Ref. 2).

The sample was held in a vacuum chamber cooled with liquid helium. Background light was completely excluded. The sample was illuminated in a controllable manner with IR light with the help of a thermal source heated to a temperature ~ 100 K. The light passed through a grid filter cooled to $T = 4.2$ K. This filter cut out the long-wavelength part of the emission spectrum from the source, with wavelengths $\lambda > 18\ \mu$m. The part of the chamber with the sample was lowered into a superconducting solenoid.

Figure 1 is a schematic diagram of the measurement part of the apparatus. The sample is part of two electric circuits. The constant measurement current flows through the first circuit; the microwave pump energy propagates through the second.

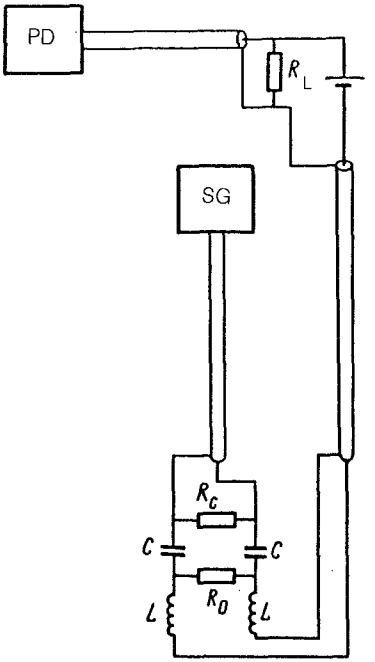

FIG. 1. Electric circuit of the measurement part of the apparatus. R_0—Test sample; C,L—matching capacitors and induction coils; R_c—matching resistance; R_L—load resistance; PD—panoramic display; SG—microwave sweep generator.

The capacitors and the induction coils are in the immediate vicinity of the sample and are used to achieve ac and dc decoupling of the circuits. A matching resistance inside the cooled chamber, at the end of the coaxial microwave line, matches the line with the output of the microwave sweep generator. The latter can scan the frequency over the range 0–600 MHz, and it can stop the sweep at a given frequency. The power of the output microwave signal can be varied from 0 to 50 mW. In the experiments we measured the conductivity of the sample as a function of the IR light intensity, the frequency and amplitude of the microwave pump, and the strenght of the applied magnetic and electric fields.

The sample was cooled in darkness to $T = 4.2$ K. The IR light source was then turned on, and the time evolution of the $\sigma(\omega)$ curve was recorded. Results found in this manner are shown by curves 1–3 in Fig. 2. With increasing duration of the exposure to the IR light, the general increase in the conductivity seen on the $\sigma(\omega)$ curve is joined by a peak, at $\sim$280 MHz. The shape of this peak does not change as the rate or method of scanning the microwave frequency is varied.

After the IR light is turned off, the conductivity of the alloy undergoes a slow relaxation. The rate of this relaxation is quite sensitive to the microwave frequency: The rate is considerably lower at frequencies corresponding to the resonance of the conductivity than elsewhere. As a result, the half-width of the conductivity peak decreases, and a state may be reached in which (away from the resonance) the conductivity of the sample is much lower than near the peak (curve 4 in Fig. 2). This is a stable state, in the sense that it is reproduced when the microwave pump is turned off for a long time and then turned on again.

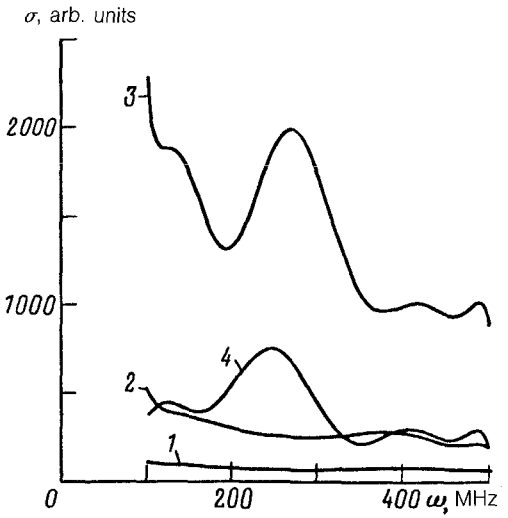

FIG. 2. Evolution of the curve of the sample conductivity σ versus the microwave pump frequency ω as the duration of the exposure to the IR light is increased (curves 1—3) and after relaxation to a metastable state (curve 4).

The amplitude and frequency of the microwave pump affect the relaxation process. When the frequency scan is stopped at the peak, at 280 MHz, the relaxation rate increases. An increase in the pump amplitude has the same consequences. If the microwave frequency is instead stopped away from the peak, the pump has no significant effect on the relaxation, aside from the dependence on the pump amplitude.

The metastable state of the sample which was found served as the starting point for some further experiments. During further IR illumination, the sensitivity of the conductivity near the peak on the $\sigma(\omega)$ curve to the IR light turned out to be much higher than that of the original dark state of the material. This is true in the regime in which the microwave frequency is scanned from 0 to 600 MHz, and it is also true in the case in which the scan is stopped at the resonance. The conductivity of the sample at the $\sigma(\omega)$ peak increases by 10^{-3} S/cm over a time of 10 s when the temperature of the thermal IR source is $T^* = 75$ K. If the sample in the dark state is illuminated, the same increase in the conductivity occurs at $T^* = 90$ K during the given exposure.

When a magnetic field $H < 0.1$ T is applied, the height of the peak at 280 MHz decreases sharply. As H is increased further, the peak moves down the ω scale. At $H = 4$ T, the peak is at 50 MHz. If the ω sweep is stopped at the resonance, the conductivity of the alloy increases as time elapses, in contrast with the behavior in a zero field.

A change in the magnitude of the supply voltage in the circuit of the sample leads to a change in the height of the resonance, without having any effect on its frequency or width.

The energy corresponding to the frequency of the microwave resonance is considerably lower than any of the characteristic energies of this material (the band gap, the impurity gap, the energy of a transverse optical phonon, etc.). Moreover, the substantial shift of the frequency of the $\sigma(\omega)$ peak in a magnetic field is evidence that the

effect stems from properties of the sample itself, not from the electric circuit of which it is part.

It is unlikely that the resonance would be due to a motion of strong-field domains in the sample. The reason is that in this case one would expect the frequency of the resonance to be a strong function of the voltage applied to the sample, but experiments reveal that this is not the case.

We believe that the microwave resonance described here is of the same nature as the microwave stimulation of photoconductivity,[3] stemming from a relaxation of photoexcited electrons to one-electron metastable impurity states.[4–6] Our reasoning is that the resonance is not observed if the sample is not subjected to a preliminary photoexcitation. Consequently, the effect stems from electrons which are generated by the IR light and which then localize in some impurity state other than the ground state. During the application of the microwave pump in a certain frequency range, the barriers W_{10} and W_{12} which separate the states E_1 from the band states and the two-electron states apparently acquire a resonant transmission (Fig. 3). As a result, (first) when the microwave sweep is stopped at the peak, there is a sharp acceleration of the recombination of free electrons, both to the impurity ground state and to the metastable state. Second, the essential disappearance of the barrier W_{10} at these frequencies has the consequence that the carriers in the metastable state delocalize and begin to take part in the conduction. When the microwave frequency is moved away from the resonance, these electrons quickly return to the one-electron states.

The effect of the magnetic field on the frequency of the conductivity peak also

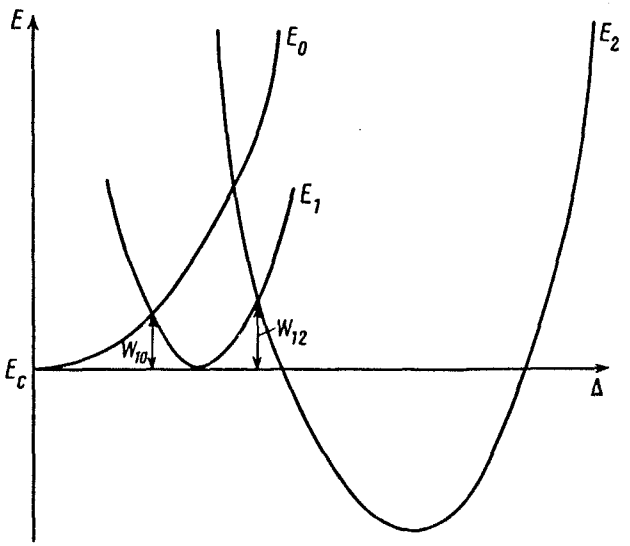

FIG. 3. Configuration diagram of the $Pb_{1-x}Sn_xTe(In)$ alloys. Δ—Configuration coordinate; $E_{0,1,2}$—curves corresponding to states of the system with 0, 1, and 2 localized electrons; W_{10} and W_{12}—barriers separating a one-electron impurity state from a state with a delocalized electron and with two localized electrons, respectively.[4–6]

supports our suggestion regarding the nature of the resonance. Specifically, the relative positions of level E_1 and the bottom of the conduction band and thus the height and shape of barrier W_{10} depend strongly on the magnetic field, as was shown in Ref. 5. It is then quite natural that the position of the resonance would be determined by the value of H. If the effect were instead due to a resonant excitation of lattice vibrations, we would hardly expect such a strong field dependence of the resonant frequency.

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