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Hopping photoconductivity and the effectiveness of phonon detection in GaAs:Zn bolometers

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Abstract

We have studied the effect of white light on hopping conduction and the effectiveness of non-equilibrium phonon detection in Zn-doped GaAs bolometers over the temperature range $1.35\ \mathrm{K} \leqslant T \leqslant 2.15\ \mathrm{K}$. The temperature dependence of the low electric field resistance indicates that the mechanism of conduction is due to variable range hopping. Using a heat-pulse technique we show that the sensitivity of a GaAs:Zn bolometer with an acceptor concentration, $n_a = 4.2 \times 10^{17}\ \mathrm{cm}^{-3}$ is significantly enhanced in the presence of suitably applied irradiation, despite the value of its temperature coefficient of resistance, $\alpha(T) = (1/R)(\partial R/\partial T)$, actually being decreased by light. It is proposed that the effect of light is to populate excited states of the acceptors, which have larger wave functions and hence show enhanced hopping.

Keywords: Hopping; Phonons; GaAs; Semiconductors

1. Introduction

The generally accepted theory of charge transport in semiconductor bolometric detectors at sufficient low temperatures, and in the limit of low electric fields, is the variable range electron hopping (VRH) mechanisms of the form, $R(T) = R_0(T)\exp(T_0/T)^n$, where, the exponent $n = 1/4$ for a non-interacting system with constant density of states at the Fermi level, and $n = 1/2$ for a parabolic Coulomb gap appearing as a consequence of long-range Coulomb interactions between localized charge carriers [1]. The factor R_0 is temperature dependent pre-exponent and T_0 is a constant having the dimensions of temperature.

Photoconduction of semiconductors is in most cases assumed to be produced by free carriers in extended states. There are, however, examples of photoconduction in semiconductors wherein the absorption of photons facilitates hopping between spatially localized states [2]. In the presence of suitable illumination, photons may play a role similar to that of phonons at sufficiently low temperature, giving rise to photo-assisted hopping which ensures energy conservation for transitions between states. For a monochromatic electromagnetic wave, the contribution to the conductivity from the hops in which only photons take part is small compared with the contribution of the hops stimulated by both phonons and photons [3]. Hops stimulated by both phonons and photons are of particular interest because the photon energy is not limited by Debye temperature and, consequently, there are no energy limitations on the single-phonon process and long distance hops are no longer obligatory. An electron can hop from a given site of energy E_{hop} absorbing photons, if and only if there is another state of energy in the interval $\hbar\Delta\omega$ near $E_{\mathrm{hop}} + \hbar\omega$, ω being the frequency of the electromagnetic wave.

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Secondly, the number of photons is independent of the temperature.

In the absence of light, at a temperature *T*, the characteristic Mott's phonon-assisted hopping energy, E_{hop}, is of the order $k_{\mathrm{B}}T(T_0/T)^{1/4}$ (for example, see [4]). The parameter T_0 in Mott's law is defined by $T_0 = \beta/E_{\mathrm{F}}a^3$, where β is a numerical coefficient and *a* is the wavefunction localization radius [5]. Light introduces the photon energy, $\hbar\omega$. When $k_{\mathrm{B}}T(T_0/T)^{1/4}$ exceeds $\hbar\omega$, the effect of light on hopping conduction is small and the Mott temperature dependence remains valid. For the case of weak illumination, when $k_{\mathrm{B}}T(T_0/T)^{1/4}$ is less than $\hbar\omega$, the electrons and holes excited from neutral centers by the light can hop from a given site by absorbing $\hbar\omega$. The electrons and holes excited states are also localized, although their localization radius is substantially larger than in the ground state. The overlapping leads to high probability of electron- (or hole-) jumps from one impurity center to another, without going through the band – hopping photoconductivity. This means that frequency of light ω should satisfy the conditions $\hbar\omega < E_{\mathrm{c}} - E_{\mathrm{F}}$, or $\hbar\omega < E_{\mathrm{F}} - E_{\mathrm{v}}$. On the other hand, the electron-hole pair can first be excited to the mobility edges and then captured into the empty states of the impurity band if $\hbar\omega > E_{\mathrm{c}} - E_{\mathrm{F}}$ or $\hbar\omega > E_{\mathrm{F}} - E_{\mathrm{v}}$. In this paper, we report the effect of white light on hopping conduction and the effectiveness of non-equilibrium phonon detection in Zn-doped GaAs bolometers at low temperatures.

2. Experimental details

Bolometric samples of high-purity melt-doped GaAs:Zn with acceptor density $n_{\mathrm{a}} = 4.2 \times 10^{17}\ \mathrm{cm}^{-3}$ were cut from a single α-crystal wafer of thickness 0.5 mm. Typical dimensions of the bolometers were $2 \times 5\ \mathrm{mm}^2$. Zinc is shallow acceptor in GaAs with the ionization energy ε_{a} of 31 meV.

Hopping photoconductivity was studied in the temperature range $1.35 \leqslant T \leqslant 2.15$ K, in a light–tight computer-controlled pumped cryostat. The samples were illuminated by white light of up to 3460 lux, which was fed into the cryostat via an optical fiber, and exposed perpendicular to the plane of the bolometer. The commercial Eurotec Light source E150 with a tungsten bulb housed in a shinny reflecting-walled box designed to focus the light beam onto a small outlet aperture, approximately 3.5 mm in diameter, was used as the source. The aperture was coupled directly to one end of the fiber nose. Prior to insertion into the cryostat, the light intensity through the fiber was calibrated using a commercial Digital LX-107-Light meter. The effective light intensity was varied with standard variac. Intensity of different colours of light was also calibrated in lux, but very low values of intensities were measured using the near monochromatic light, presumably because of the low detector signal intensities. Experiments with a source of monochromatic light with higher intensity (comparable with the integrated intensity of the white light used in the present work) should help determine the wavelength dependent response of the detector. This area of research is still open and more work is being planned. For efficient cooling, the bolometric sample was kept in direct contact with liquid–^{4}He. Under the illumination conditions used in this work, the sample heating resulting from the absorption of light can be neglected even for maximum intensity of 3460 lux ($\approx$0.5 mW cm^{-2} at 555 nm) at $T = 1.7$ K (approximately the average of the temperature range studied). This is because both the vapour pressure of the ^{4}He phase in the cryostat and the lattice temperature remain unchanged over the excitation range of 0.35– 4.0 mW cm^{-2} [6].

For the *R*–*T* measurements, the samples were thoroughly cleaned with organic solvents using a standard procedure [5]. Any oxidized layers present on the sample surface were removed by soaking them in 10% HCl. Four ohmic point-contacts arranged in line through the center of the samples were made by vacuum deposition of Au. Copper leads, 0.05 mm in diameter, were silver-pasted to the contact pads. Standard four-point dc resistance measurements were employed using high-impedance voltmeters for the *R*–*T* measurements. The temperature was measured with a four-wire calibrated GR-200A germanium resistance thermometer (GRT) from LakeShore Cryotronics. This GRT was calibrated directly with very high accuracy using the McLeod pressure gauge and the 1958 ^{4}He vapour pressure temperature scale [7]. For these calibrations, the pumping rate was kept very low to ensure that the liquid was in equilibrium with the vapour pressure. The accuracy of the calibration as checked against the manufacturer's data was found to be accurate within ±18 mK.

For phonon experiments, one face of the bolometer was acoustically bonded with a thin (<1 μm) layer of epoxy resin onto one face of an undoped, standard polished [1 0 0] Si wafer of thickness 500 μm. A thin aluminum film, typically 15–25 nm, vacuum-evaporated on the reverse side of the silicon crystal was heated by electric current pulse. Heat-pulses produced in the film propagate through the crystal and the interface, and are detected by the bolometer. The heat-pulses reaching the bolometer were typically a few microwatts in magnitude and a few nanoseconds in duration, following a Planck's distribution for phonons with approximate temperature of 17 K (peak frequency 1 THz).

3. Results and discussion

The ln *R* (*R* being the resistance of the bolometer) in the dark and under two levels of illuminations *J*, is plotted in Fig. 1 versus $T^{-1/4}$. For clarity, we show only two curves for the sample under illumination, first, for illumination $J_2 = 3460$ lux, representing the maximum optical flux accessible to our experiments, and second, for an intermediate value of flux, $J_1 = 500$ lux. J_0 denotes zero intensity (=0 lux or dark). By least square fitting of the data with the expression $R(T) = R_0(T)\exp(T_0/T)^n$ with *n* taking the values 1, ½ and ¼, we found that the exponents of the temperature dependence of dark conductivity and photoconductivity were similar. The ohmic *R*(*T*) characteristic in

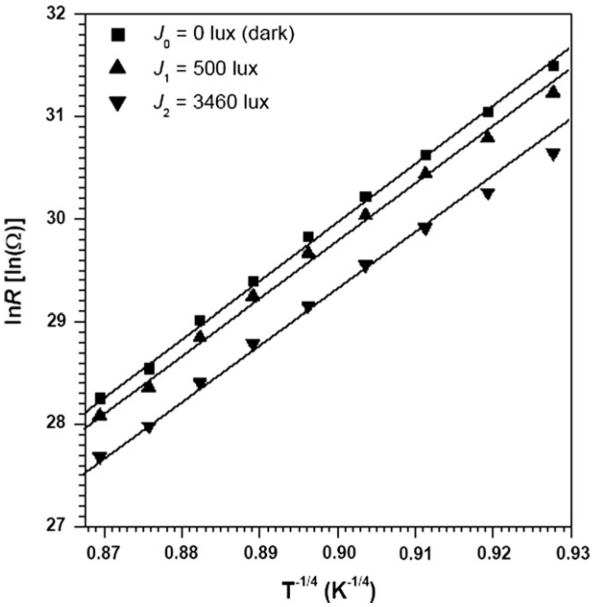

Fig. 1. Temperature dependence of ln(R) versus $T^{-1/4}$ for different illumination intensities. J_0 corresponds to zero intensity, J_1 the intermediate intensity (500 lux) and J_2 the maximum intensity (3460 lux). The data have been collected at the temperature 1.4 K of the phonon experiments with a bias current of 1 μA.

both cases were found to obey the $\ln R \propto T^{-1/4}$ law for conduction by VRH for a non-interacting system with a constant density of states at the Fermi level. Further, the values of T_0 determined from the slopes of the best-fit straight lines in Fig. 1 are 3.5×10^5 K (in dark, i.e., for J_0), 3.1×10^5 K (for J_1) and 2.5×10^5 K (for J_2). Thus, an increase in excitation intensity appears to reduce the value of T_0, which indicates some reduction in the temperature factor, $\xi_c = (T_0/T)^{1/4}$ and the mean hopping distance ($R'_{\text{hop}}(T) \approx (3/8)a^3\xi_c$). Although the temperature range studied is too small to distinguish the $n = ¼$ dependence from the $n = ½$ convincingly, the observed photoconductivity appeared to be due to variable range hopping, which may suggest that the photo-holes are concentrated in the localized states. Thus the effect of irradiation with white light seems to enable the holes to hop with reduced energy, possibly by making available empty final states near the impurity band. The fact that the Mott temperature dependence remains valid under illumination suggests that the photon energy reaching the sample exceeds any possible electric-field effects on hopping that may be induced by light, and since $\hbar\omega$ exceeds $k_BT(T_0/T)^{1/4}$ ($\hbar\omega$ is approximately three orders of magnitude greater than $k_BT(T_0/T)^{1/4}$, for the range of frequencies in white light), holes excited by the light from neutral centers by absorbing $\hbar\omega$ can contribute to conduction.

In the temperature range investigated, any other photoconductive process, such as interband excitation, appears to be making a negligible contribution, presumably because interband relaxation is very rapid. The steady-state decrease of T_0 can be understood as an increase of the probability of tunneling and an apparent increase in E_F arising from optical depopulation of acceptor states within the hopping range, which will also modify the pre-exponent, R_0(T). At the temperature of the phonon experiments (1.4 K), the values of the temperature coefficients of resistance, $\alpha(T) = (1/R)(\partial R/\partial T)$, ranged from -3.5 to $-2.1\ \text{K}^{-1}$, in all the samples, for the maximum optical flux, J_2 (=3460 lux). For zero intensity, however, these extreme values were -4.4 and $-3.1\ \text{K}^{-1}$. These results suggest that the sensitivity of a bolometer element might be significantly reduced by optical illumination. This effect could be important at lower temperatures where the bolometer resistance and the hopping distance (R_{hop}) can be quite large. The immediate expectation here would be that the effect of light is to change the phonon responsivity by almost the same factor as the slope of the resistivity.

In Fig. 2, a typical heat-pulse response of phonons detected by the bolometer is shown (inverted) following heat-pulse excitation at 1.4 K and with a bolometer bias current of 1 μA. Pulses of 50 ns duration and 1 V are supplied to the heat-pulse generator at a repetition rate of 800 Hz. The data were taken by a signal averager. The most obvious features observed in figure are a sharp initial spike (shown as BT) due to direct induction breakthrough from generator to bolometer (at 17 μs). This initial rise of the signal is the zero of the time-of-flight scale. The broader feature is due to the arrival of phonons after multiple reflections in the Si substrate. The rise time of the phonon pulse is 4 μs and the decay time approximately 12 μs.

The heat-pulse emitted by a thin film generator follows a Planck distribution at an effective temperature, $T_{\text{eff}} = T_H - T_S$, ($T_H$ and T_S are the heater and substrate temperatures, respectively) related to the power dissipated per unit area, $P(T)$, through the expression, $P(T) = B_0\left(T_H^4 - T_S^4\right) \approx B_0T_{\text{eff}}^4$, where B_0 is 203 W K^{-4} m^{-2} for an aluminum generator film on a silicon substrate [8]. The power density dissipated into the heater results in a Planck distribution of

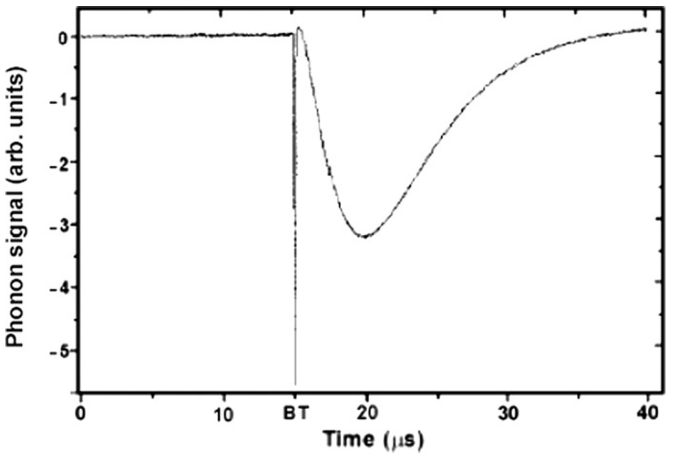

Fig. 2. Typical bolometer signal detected at T = 1.40 K, for a 10 mV input pulse power of pulse duration 50 ns, and a bolometer bias current of 1 μA. the peak marked BT (direct induction breakthrough) corresponds to the electromagnetic pick-up of the heater excitation pulse.

emitted phonons with a temperature of about 17 K, which corresponds to a dominant phonon frequency of 1 THz in the emitter heat-pulse profile.

The effect of light (Fig. 3) was to enhance the magnitude of the detected phonon signal considerably (by a factor of approximately 4) over the range of optical flux available, initially in a linear manner but eventually saturating. The heat-pulse response for increasing illumination intensity is shown in Fig. 4. The response labeled J_0 in Fig. 4 was recorded at zero intensity; others (J_1 and J_2) correspond to increasing illumination intensity. J_1 corresponds to 500 lux, and J_2 corresponds to 3460 lux. As the illumination intensity increases from J_0 to J_2, the shape of the phonon signal profile remains essentially the same (Fig. 4). This indicates that phonons generated by the photons produce the same type of response in the bolometer as those generated under zero illumination (or, in the dark). As seen in the figure, the amplitude increases considerably at lower intensities. Further increase of the illumination intensity did not lead to any pronounced increase in the pulse height.

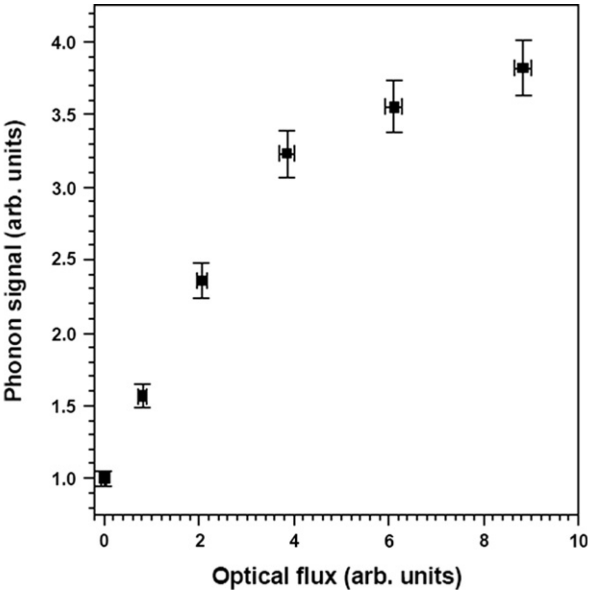

Fig. 3. Variation of bolometer output voltage with optical flux at 1.40 K. The bolometer bias current was 1 μA and the voltage pulse was of 50 ns duration.

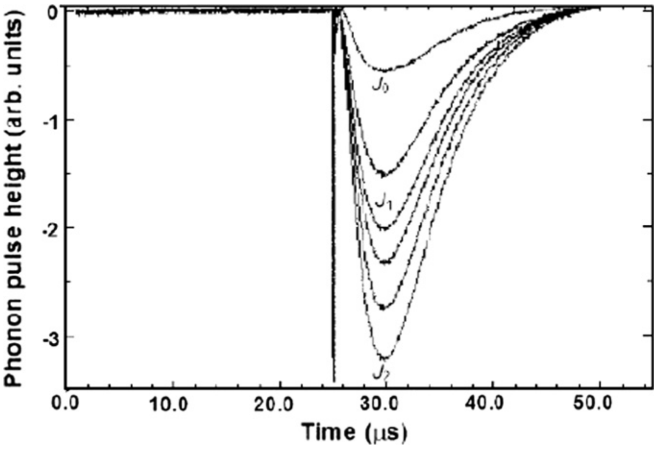

Fig. 4. The heat-pulse response of the detector with increasing optical flux.

4. Conclusions

An inverse linear relationship between the enhancement of the phonon signal and the values of T_0 has been observed in the GaAs:Zn bolometers constructed. The most plausible explanation of this result is that the probability of absorbing the high energy phonons in the tunneling process is much increased, compared to that for thermal phonons, by the presence of photons [9]. Photo-excited carriers that absorb thermal phonons do not have to hop as far to find a state of the correct energy, decreasing therefore the temperature dependence. This might occur if illumination also populated excited impurity states, known to have binding energies at 9 and 5 meV and hence less localized [10]. Because of their higher frequencies, the non-equilibrium phonons could contribute a greater energy in the hopping process. Thus transitions taking place between spatially closer neighboring sites that have larger energy splittings would be permitted. If the high-energy phonons couple directly to the carriers without being thermalised first, the increase in tunneling probability may lead to larger pulses. In our experiments, the white light used for excitation had the energy range $\hbar\omega \approx 1.7$–3.1 eV (mean value of $\approx$2.2 eV, for 555 nm), whereas, $E_F - E_v$ or $E_c - E_F \approx 0.7$ eV. Thus, $\hbar\omega > E_F - E_v$ (or $\hbar\omega > E_c - E_F$), meaning that the electron-hole pair were excited first to the mobility edges and then captured into the empty states of the impurity band leading to photon induced variable range hopping conductivity. If photon energies of $\hbar\omega < E_F - E_v$ (or $\hbar\omega < E_c - E_F$) were used for excitation, then photo-carriers might have been excited to levels that are either sufficiently close to E_F or at the mobility edges. In these cases, photon-stimulated hopping conductivity may no longer be of variable range. Carriers would be more likely to hop to the nearest empty sites generated by photons. In this instance, the most likely dominant conductivity mechanism is nearest-neighbor hopping. An implication of these results is that in lightly doped GaAs:Zn bolometer, and perhaps also in others based on a similar mechanism, the response may be greatly enhanced, by the exposure to illumination of low intensities and power although the resulting phonon response may not necessarily be linear. One important feature of the experiment is that significant signal enhancement is only observed when the bolometer is weakly excited, typically with illumination intensities of up to 500 lux. This level of intensity permits observation of unambiguous effects of light. Higher values of intensity would suppress the signal measured across absorber.

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