Fast photoresponse and high parallel transport in *n*-type PbTe/PbEuTe quantum wells

F. S. Pena, M. L. Peres*, M. J. P. Pirralho*, D. A. W. Soares*, C. I. Fornari**, P. H. O. Rappl**, E. Abramof***

* Instituto de Física e Química, Universidade Federal de Itajubá, Itajubá, MG CEP 37500-903, Brazil
** Laboratório Associado de Sensores e Materiais, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, PB 515, SP CEP 12201-970, Brazil

Abstract

We investigated the photoconductivity effect in *n*-type PbTe/$Pb_{0.88}Eu_{0.12}Te$ quantum wells for a temperature range of 300 – 10K using infrared light. The measurements revealed that at high temperatures the photoresponse has small amplitude. As temperature decreases to T~75K, however, the photoconductivity amplitude increases reaching a maximum value 10 times higher than the original value before illumination. From Hall measurements performed under dark and light conditions we show that this effect is a result of carrier concentration increase under illumination. Unexpectedly, for further reducing of temperature, the amplitude starts to decrease again. The electrical resistance profiles indicate that the transport occurs through barriers and well that behave as two parallel channels. For temperatures below 75K, transport is more effective in the quantum well, where the signal reduction can be associated to the electron-electron scattering due to the increase of carrier concentration that occurs under illumination. We also used the random potential model to explain the origin of the persistent effect observed in the photoconductivity curves.

PbTe based quantum wells (QW's) have been widely used to fabricate infrared (IR) lasers, IR detectors and thermogenerators[1-4]. Also, due to the large interest in spintronic devices, considerable efforts are dedicated lately to investigation of spin-orbit (SO) coupling and quantum Hall effect in different nanostructures and PbTe based structures have emerged as potential candidates for the development of spintronic devices[5-9]. In fact, Peres et al. (2014)[10] reported a large Rashba spin-orbit coupling effect in *n*-type PbTe quantum wells and Chitta et al. (2005)[11] showed a complex transport mechanism in PbTe QWs due to the multivalley band structure that leads to an unusual quantum Hall effect. From the practical application point of view, the effect of disorder on electrical transport in PbTe based devices is an important issue that lacks further investigation. In order to develop high performance sensors, it is mandatory to reduce the noise intensity and increase the electrical response. In the specific case of PbTe QW´s, the doping of PbTe layer increases the carrier concentration to improve the electrical signal but, on the other hand, also introduces additional disorder that can compromise the efficiency of the device by increasing the noise level depending on the operation temperature. Instead of the PbTe layer, the $Pb_{1-x}Eu_xTe$ barrier is doped with bismuth in this work to avoid such scenario. In this way, we expect that a spontaneous carrier transfer occurs from the barriers to the QW as temperature is lowered. In fact, this process is confirmed here by experimental data. However, an anomalous behavior of the photoconductivity signal is observed, presenting profiles that are completely different in different temperature regions, indicating the complexity of electrical transport in such structures.

PbTe is a narrow gap semiconductor with sodium chloride crystalline structure. The valence band maximum and the conduction band minimum are located at the L point of the Brillouin zone, possessing a complex nonparabolic band structure and strong anisotropic multiple valleys, consisting of four ellipsoids of revolution[12]. Besides, due to its high dielectric constant value (~1400 at 4.2K), high carriers mobility can be achieved since the scattering from ionized impurities is considerably reduced. The introduction of Eu atoms to form the $Pb_{1-x}Eu_xTe$ alloy drastically alters the properties described above. A metal – insulator transition is observed for $Pb_{1-x}Eu_xTe$ films at $x \approx 0.06$, for p-type samples[13], and at $x \approx 0.10$ for n-type films[14]. Also, the introduction of Eu causes disorder that gives rise to Anderson localization, which can be investigated through magnetoresistance measurements at low temperatures[15]. At higher temperatures, the effect of disorder in such films can be systematically investigated using photoconductivity measurements, which allows one to determine the energy of the trap level caused by disorder states[16-19].

In this paper, we present photoconductivity measurements performed on a single 10nm $PbTe/Pb_{0.88}Eu_{0.12}Te$ quantum well for temperatures from 300 down to 10K using infrared light. The measurements revealed that at high temperatures the photoresponse has small amplitude. As temperature reduces to T~75K, the amplitude reaches a maximum value 10 times higher than the original value before illumination. Unexpectedly, when temperature reduces below 75K, the photoconductivity amplitude starts to decrease again. We show that this effect is a result of transport through barriers and quantum well that behave as two parallel channels. For temperatures below 75K, the transport is more effective in the quantum well and the signal decrease can be associated to the electron-electron scattering due to the increase of carrier concentration that occurs under illumination. We also compare the data obtained from another

QW with well width of 14nm and we observed the same profiles. We hope these results can give support to the development of optical-electronic devices based on PbTe structures.

The 10nm thick $PbTe/Pb_{0,88}Eu_{0,12}Te$:Bi quantum well sample was grown by molecular beam epitaxy on (111) cleaved BaF_2 substrates. The sample structure consists of 2.3 μm thick $Pb_{0,88}Eu_{0,12}Te$ buffer layer grown on top of the (111) BaF_2 substrate and a 10nm PbTe layer, grown with off-stoichiometry Pb rich source to guarantee *n*-type character, embedded between two 30nm $Pb_{0,88}Eu_{0,12}Te$ barriers doped with bismuth that also exhibit *n*-type characteristic. To make the electrical contacts, small indium pellets are placed on the sample surface in the Van der Pauw geometry together with Au wires. This is set on a hot plate heated up to 180°C. In this way, the indium diffuses through the heterostructure and crosses the layers (barriers and well)[20]. The sample structure is drawn in Figure 1(a). For illumination of the sample, an infrared light emitting diode with peak wavelength of 940 nm and 12 mW/m^2 was used for the photoconductivity experiments. Resistivity and Hall measurements were performed in order to obtain the transport parameters under illumination and dark conditions.

The energy gap value $E_g(x,T)$, at 77K, is 190meV and 727meV for the well and the barrier, respectively, according to $E_g(x,T) = 189.7 + 0.48[T^2/T + 29](1 - 7.56x) + 4480x$, where x is the Eu content in the alloy and T is the temperature[21]. The simplified illustration of energy band diagram of this quantum well is shown in Figure 1(b), assuming 55:45 conduction to valence band offset[8], resulting in a potential barrier with height energy of 295meV for the conduction band (ΔE_c) and 242meV for the valence band (ΔE_v). The confinement energy levels in the well conduction band, considering the longitudinal and the oblique valleys, were calculated using the procedure presented in reference 10 and are displayed in figure 1(c) in a simplified representative illustration. The values are 11meV, 38meV, 78meV, 123meV, 170meV and 219meV for the levels derived from the longitudinal valley and 45meV and 154meV for the confined levels from the oblique valleys.

Figure 2(a) presents the normalized photoconductivity (σ/σ_0, where σ_0 is the electrical conductivity under dark conditions) measured for 10nm PbTe/$Pb_{0,88}Eu_{0,12}Te$ QW at temperatures ranging from 10K up to 300K using infrared illumination. The illumination is switched on at $t = 0$ and off at $t = 100$s. At high temperatures, photoconductivity presents small amplitude (< 1%) but, as temperature reduces, a huge increase of photoresponse is observed. At T=75K, the maximum amplitude reaches a value 10 times higher than the original value before illumination. On the other hand, according to this figure, further decreasing the temperature leads to a reduction of photoconductivity amplitude. The inset in figure 2(a) details the temperature dependence of the photoconductivity amplitude (σ_M/σ_0), where σ_M is the maximum photoconductivity value. This behavior is unexpected since for most experiments in narrow gap semiconductors photoconductivity amplitude increases as temperatures decreases[11]. This effect can be related to the QW structure that can allow transport via combination of two channels, in this case the barrier and the well itself.

Figure 2(b) presents the electrical resistivity ρ as a function of temperature under dark (off) and light (on) conditions. Without illumination (open circles), ρ decreases smoothly until 100K and drops about one order of magnitude for lower temperatures down to 10K. The insert in the figure shows the derivative of electrical resistivity with respect to temperature, where it is possible to observe a rapid increase below 100K reaching a maximum around 75K and further decrease for lower temperatures. These curves suggest that the transport in the modulated structure can be described by a combination of contributions from barriers and well, like in a parallel association of resistors. In order to verify this assumption, we measured electrical resistivity as a function of temperature of 2 μm thick single layers identical (same composition and carrier concentration) to the constituent layers that compose the heterostructure: $Pb_{0,88}Eu_{0,12}Te$ (buffer), $Pb_{0,88}Eu_{0,12}Te$:Bi (barrier) and PbTe (well). From these measurements, we verify that $Pb_{0,88}Eu_{0,12}Te$ buffer has practically no contribution to the total resistivity, since it is insulating, and the resulting resistivity is basically a combination of the conduction through the two 30nm thick barriers and 10nm thick well (see figure S2(b) in supplementary material).

To understand the conduction through the $Pb_{0,88}Eu_{0,12}Te$ doped with bismuth, we measured the carrier concentration as a function of temperature of a 2.3 μm thick $Pb_{0,88}Eu_{0,12}Te$:Bi film. We obtained an activation energy that relates to a donor level located around 6.3meV below conduction band edge, which corresponds to a thermal energy k_BT with a temperature of 73K. This value is very close to the temperature where the derivative of electrical resistivity with respect to temperature presented in insert of figure 2(b) is maximum. This analysis shows that at high temperatures (T>75K, k_BT>6.3meV), transport occurs through barriers and well. Otherwise, for T<75K (k_BT<6.3meV), electrons are transferred from the donor state in $Pb_{0,88}Eu_{0.12}Te$:Bi barriers to the PbTe layer and the transport is mainly through the well. The effect of carriers transference from barriers to well has been already reported in literature for similar heterostructures based in PbTe compounds[22].

Under illumination, open circles in figure 2(b), the drop in resistivity occurs below 200K, exhibiting a huge effect of light in transport properties. Infrared light (λ~940nm) promotes carriers directly from valence to conduction bands in PbTe well and $Pb_{0,88}Eu_{0,12}Te$:Bi barriers.

However, the recombination rates depend on temperature. At temperatures higher than 200K, recombination rates are high enough to reduce considerably the photoconduction effect. Hall measurements performed on the QW structure, under dark and light conditions, corroborates very well with this result. As shown in figure 3(a), an expressive increase in electron concentration under illumination (open squares) is observed only below 200K. For T>200K, due to the high recombination rates, the photogenerated carriers practically do not contribute to the total electron concentration. In addition, the curve without illumination (open circles) in figure 3(a) also exhibits an increase in carrier concentration for T<80K, which is due to the carrier transfer from barriers to well, in accordance to the previous discussion.

Figure 3(b) presents the carrier mobility of the PbTe/$Pb_{0,88}Eu_{0.12}Te$ QW structure as a function of temperature. Without illumination (open circles), mobility increases in the whole temperature range presenting a small saturation close to 10K. Under illumination (open squares), the mobility curve is basically the same as the one for dark conditions in the temperature range of 300K to 200K. In the region of 200K to 80K, one observes an increase of the mobility in relation to the curve without illumination and, for 10K<T<80K, mobility under illumination becomes smaller than the curve in dark conditions. The decrease of carrier mobility indicates that the drop in the photoconductivity amplitude between 80K and 10K observed in figure 2(a) is caused by an additional scattering mechanism, probably electron-electron interaction due to excess of photogenerated carriers. In addition, scattering mechanism can be further enhanced by the contribution from multiple valleys in the quantum well [23]. This can be verified by calculating the position of the Fermi level in the quantum well at low temperatures, where the conduction in the QW structure occurs basically through the PbTe well. This can be derived taking into account the mass anisotropy and integrating the density of states for all possible subbands (one longitudinal and three oblique valleys) according to $n = \int_0^{\varepsilon_F} d\varepsilon \frac{m_l}{\pi\hbar^2} + 3\int_0^{\varepsilon_F} d\varepsilon \frac{m_o}{\pi\hbar^2}$. We found that $\varepsilon_F = \frac{n\pi\hbar^2}{(m_l+3m_o)}$, where m_l and m_o are the longitudinal and oblique effective masses, respectively[11]. At 10K, the Fermi energy calculated for the PbTe QW under dark conditions, taking $n \approx 1.55\times10^{16}m^{-2}$, is $\varepsilon_F \approx 12.3$meV. This indicates that just one longitudinal level (E_{L1}) is occupied at 10K, according to figure 1(c). This means that, under dark conditions, contribution from multiple valleys to scattering mechanism should not be observed. Under illumination, taking $n \approx 7.8\times10^{16}m^{-2}$ at 10K, we obtain $\varepsilon_F \approx 62.2$meV. In this situation, there are two longitudinal levels (E_{L1} and E_{L2}) and one oblique level (E_{O1}) occupied, as can be seen from figure 1(c). Hence, the longitudinal and the three oblique valleys contribute to transport under illumination at low temperatures. This effect leads to an enhancement of electron-electron scattering in this temperature range (10K to 80K), causing the reduction of carrier mobility and photoconductive amplitude as observed in figure 3(b) and figure 2(a), respectively.

The photoconductive effect in the PbTe/$Pb_{0,88}Eu_{0.12}Te$ QW structure can be analyzed in more detail. As the light is turned on (t = 0 in figure 2(a)), sample presented very fast photoresponse and saturation with an almost noise free signal. When light is switched off, however, the curve measured at 10K exhibits strong persistent photoconductivity effect while curve at 150K returns much faster to its original position, even though it also presents a persistent effect which is not visible in the graphic scale (see arrow in figure 2(a)). The interplay between well and barrier transport has important consequences to photoconductivity effect and trap levels inside both channels are relevant to determine the persistent effect in photoconductivity of the QW structure, As for the barrier, it is known that trap levels are present in films of PbEuTe[13,16]. Otherwise, information about trap levels in PbTe well is not available.

We can obtain information about the trap levels by analyzing the decay curves, when the light is switched off at $t = 100$s in figure 2(a), using the expression $\sigma(t) = \sigma_0 \exp(-t/\tau)$ [24]. Figure 4 exhibits the natural logarithm of recombination times, obtained from the exponential fitting to the decay curves, as a function of $1/k_BT$. As expected, the recombination time increases as temperature decreases. However, this behavior changes in the region where the transport starts to be dominated by the QW and the recombination time reduces abruptly for temperatures below ≈75K. It is possible to obtain the energy of the trap level $\Delta\varepsilon$ responsible for the persistent effect in the barriers by performing a linear fitting to the curve in Figure 4(a) considering the expression[25] $\tau = \tau_0 e^{\Delta\varepsilon/k_BT}$. The obtained value is $\Delta\varepsilon = 54meV$(±6meV). This trap level is originated from disorder present in the sample and comes mainly from Eu atoms[16]. We can consider the model of random inhomogeneities[26] and derive the energy associated to the trap level using the expression $E_t = e^2N^{2/3}/\varepsilon n^{1/3}$, where N is the impurity density, n is the carrier concentration and ε is the dielectric constant. The impurity density N can be obtained from magnetoresistance (MR) measurements. It is known that one of the effects of impurities in semiconductors is the presence of the linear magnetoresistance (LMR) effect[27] and that LMR should behave according to the expression $[\rho(B,T) - \rho(0,T)]/\rho(0,T) = N_iB/\pi n^2 e\rho(0,T)$, where $\rho(B,T)$ is the electrical resistivity as a function of magnetic field B and temperature T. We performed Hall characterization and MR measurements in a $Pb_{0,88}Eu_{0.12}Te$ film of 2.3μm thickness in order to obtain the parameters necessary to determine N from the slope of magnetoresistance curve. The used values were $\rho \approx 6.25 \times 10^{-1}\Omega cm$, $n \approx 6.0 \times 10^{17} cm^{-3}$and the slope of MR curve is $\approx 0.022T^{-1}$ approximately (see inset in Figure 4). These values give $N \approx 2.5 \times 10^{19} cm^{-3}$, which is huge value of defects when compared to $N \sim 5\times10^{17}\ cm^{-3}$ from Pirralho et al[16]. This is expected since disorder in these films increases with Eu concentration.

With these values we obtain $E_t \approx 30.5$meV which differs about 20meV from the value obtained from photoconductivity curves (≈54meV). This difference can be a result of Bi doping of the barriers that could also introduce some disorder degree. In this case, the value of 54meV is an effective value resulting from disorder caused from Eu and Bi atoms.

In conclusion, we performed photoconductivity and Hall measurements on *n*-type PbTe/$Pb_{0.88}Eu_{0.12}Te$ quantum well structure and found that photoresponse to infrared light has contributions from barriers and well. We verified that the contribution from each channel depends on the temperature region and, for high temperatures, the transport via barriers is more effective since the thermal energy is comparable to the bismuth donor level located below the $Pb_{0.88}Eu_{0.12}Te$ conduction band edge. Otherwise, at low temperatures, the transport is dominated by the conduction through the PbTe well. The temperature dependence of the photoconductivity amplitude corroborates qualitatively well with the electron concentration and Hall mobility curves obtained under dark and light conditions. We also found the presence of persistent photoconductivity effect in the whole range of temperatures measured and we were able to calculate the depth of trap energy in the barriers from the experimental data and compare to the random potential model. The values are similar, but differ due to the inclusion of Bi atoms in the barrier, which was not taken into account in the model. Besides, we showed that the decreasing of photoconductivity amplitude for temperatures below ≈75K is due to the electron-electron scattering enhanced by conduction via multiple valleys, which leads to reduction of carrier mobility.

Supplementary Material

To verify the reproducibility of the data presented so far, similar sample with 14nm thickness *n*-type PbTe/$Pb_{0.88}Eu_{0.12}Te$ QW was grown and photoconductivity measurements were performed. We performed hall measurements as a function of temperature in a $Pb_{0.88}Eu_{0.12}Te$:Bi layer to obtain the Bi donor level. We also measured the electrical resistivity as a function of temperature of 2 μm thick single layers identical (same composition and carrier concentration) to the constituent layers that compose the QW heterostructure: $Pb_{0.88}Eu_{0.12}Te$ (buffer), $Pb_{0.88}Eu_{0.12}Te$:Bi (barrier) and PbTe (well), in order to understand the conduction through the different channels in the QW structure.

See supplementary material for the results.

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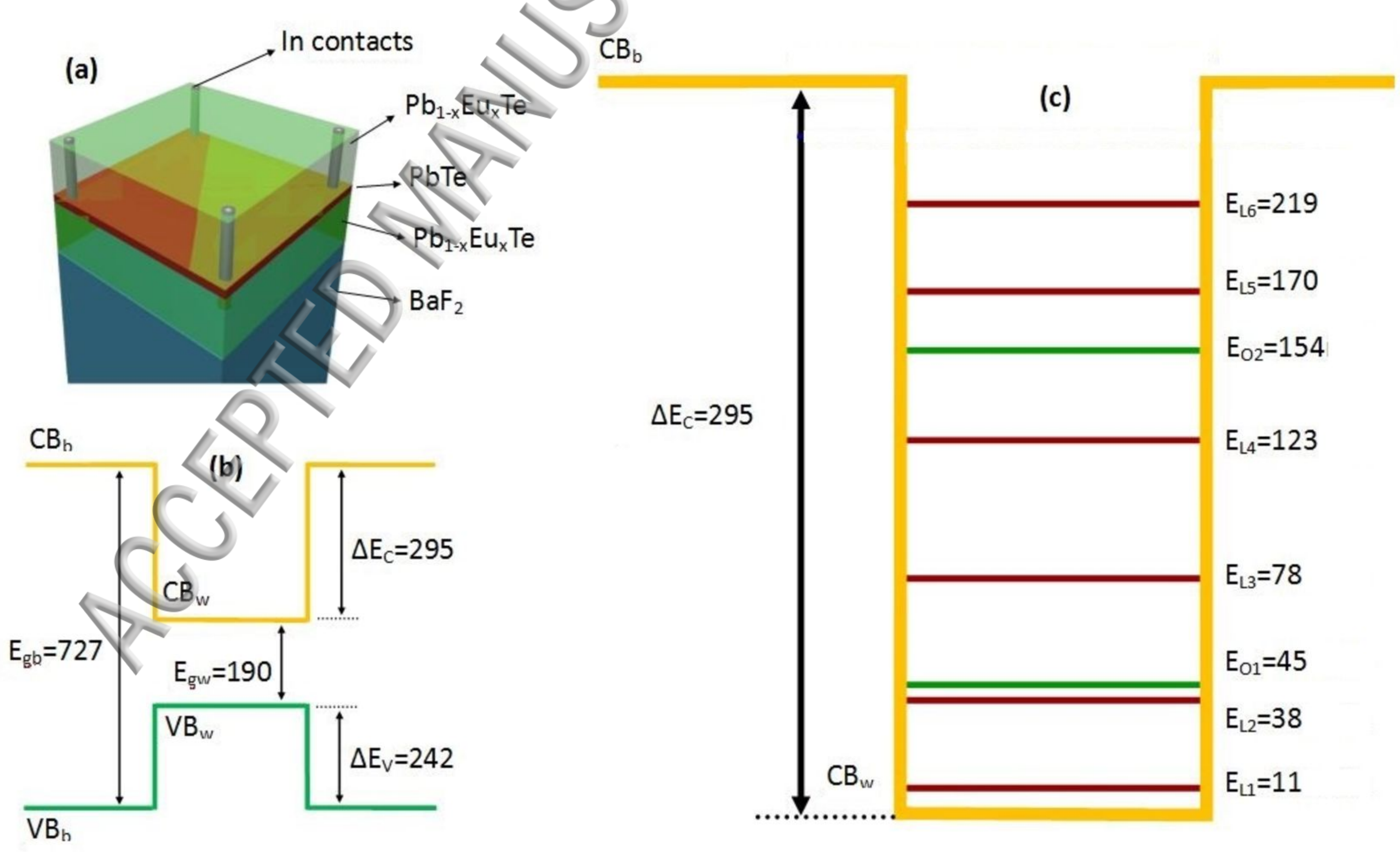
CAPTIONS

Figure 1. (a) Scheme of a $PbTe/Pb_{1-x}Eu_xTe$ quantum well structure sample with In contacts made by diffusion, following the Van der Pauw geometry. (b) Simplified illustration of energy band diagram in units of meV of a $PbTe/Pb_{0.88}Eu_{0.12}Te$ quantum well structure at 77K, where E_{gb} is the energy gap of barrier, E_{gw} is the energy gap of the well, ΔE_v and ΔE_c are the energy high of valence and conduction band barriers, respectively. (c) Simplified representative illustration of quantized energy levels inside the ≈10nm QW derived from longitudinal (L) and oblique (O) valleys, using the effective mass approximation method. All values of energy are in units of meV.

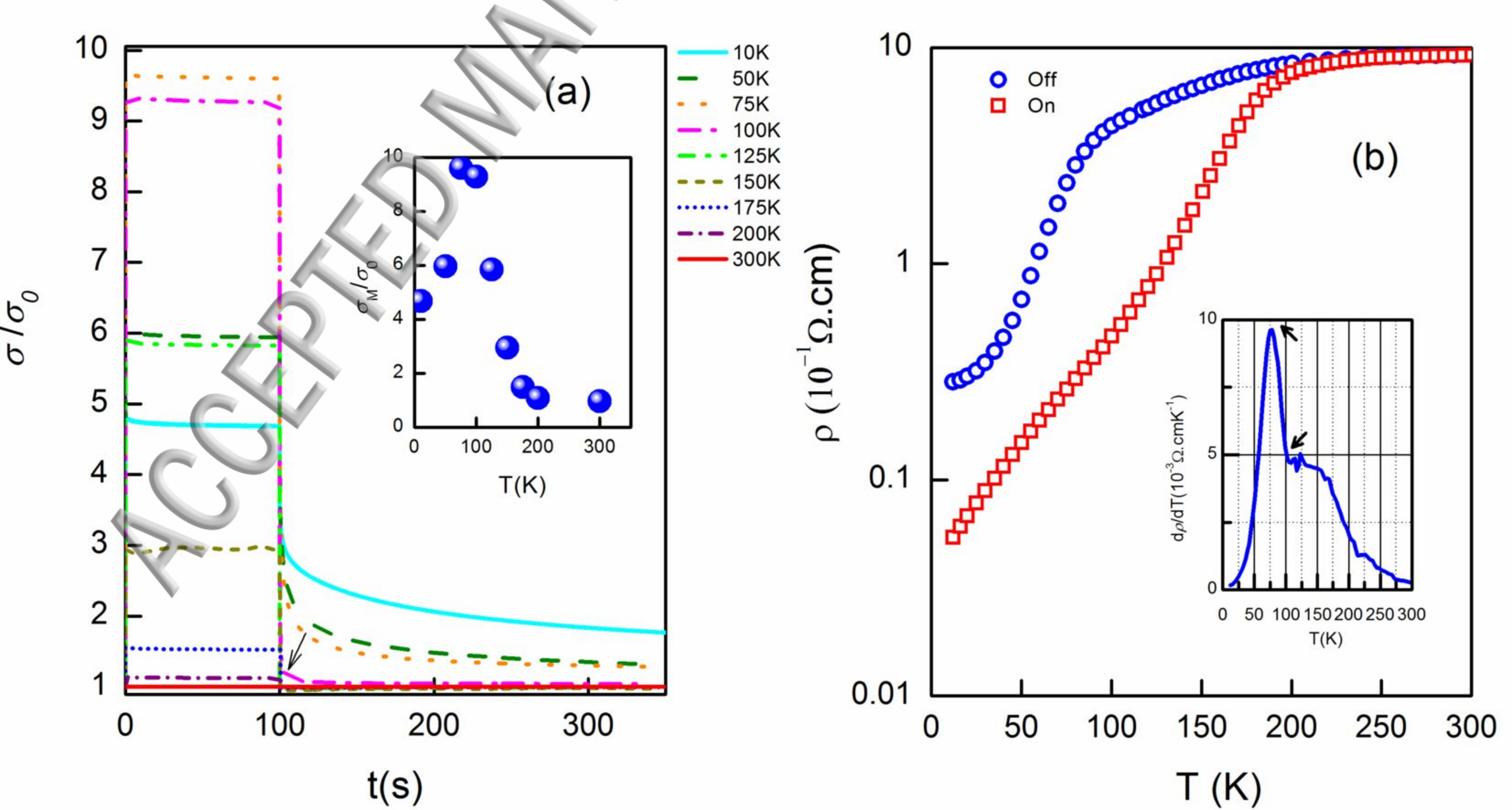
Figure 2. (a) Normalized photoconduction of the $PbTe/Pb_{0.88}Eu_{0.12}Te$ QW structure under infrared irradiation ($\lambda \sim 940$nm) for temperatures in the range of 300 down to 10K. (b) Electrical resistivity as a function of temperature showing the change of conduction channel from the barrier to the well, under dark (off) and illumination (on) conditions. The insert displays the derivative of the resistivity in respect to temperature without illumination.

Figure 3. Electron concentration (a) and Hall mobility (b) of the $PbTe/Pb_{0.88}Eu_{0.12}Te$ QW structure measured as a function of temperature with the infrared light turned off and on.

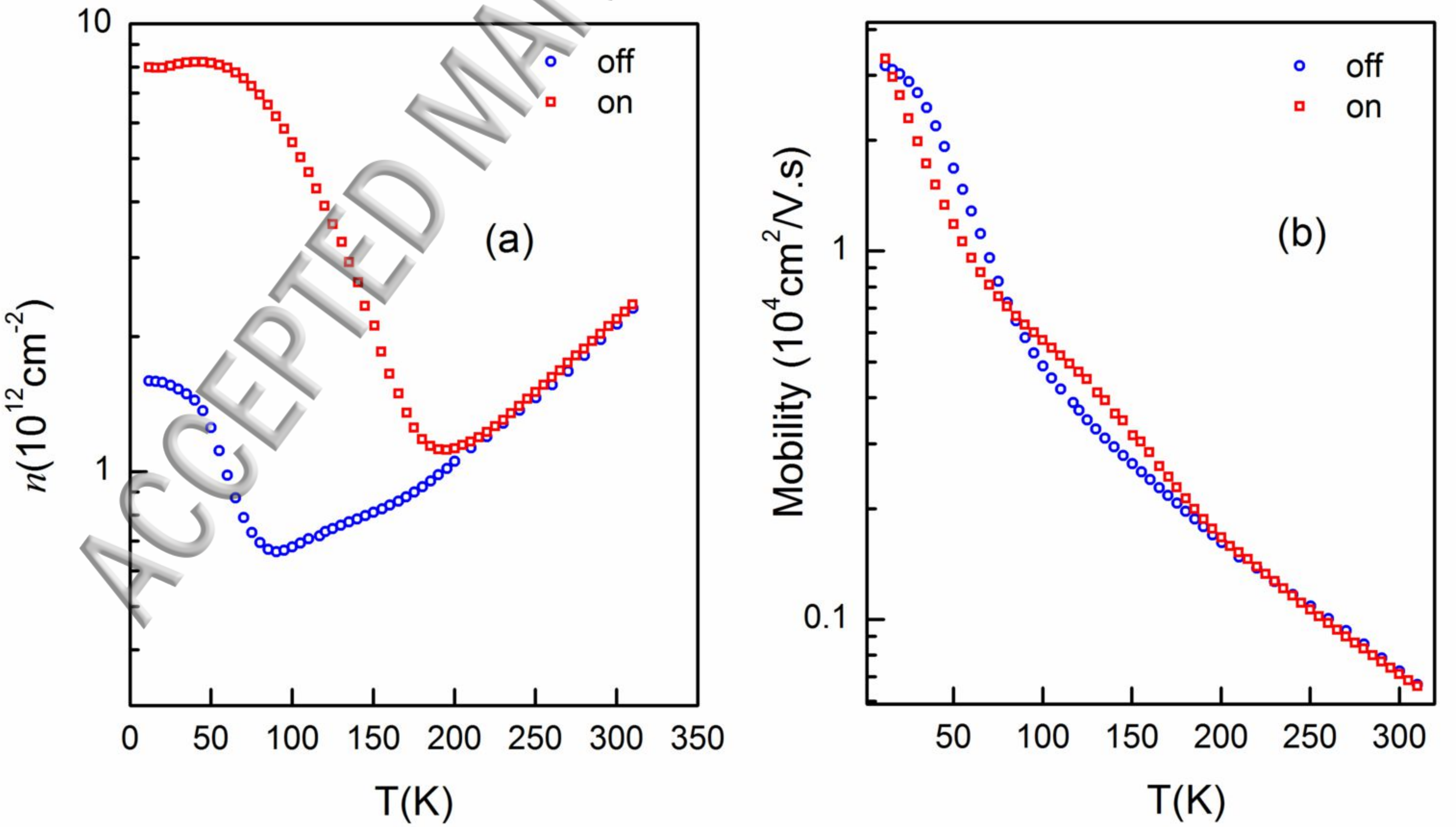
Figure 4. Natural logarithm of recombination time of the $PbTe/Pb_{0.88}Eu_{0.12}Te$ QW structure, obtained from the exponential fitting to the decay curves in photoconduction, as a function of $1/k_BT$. The blue line corresponds to a linear fit for $T > 100$K, from which the activation energy relative to a trap level in $Pb_{0.88}Eu_{0.12}Te$ is determined. The inset shows the slope of the magnetoresistance curve for a $Pb_{0.88}Eu_{0.12}Te$ film with 2.3μm of thickness.



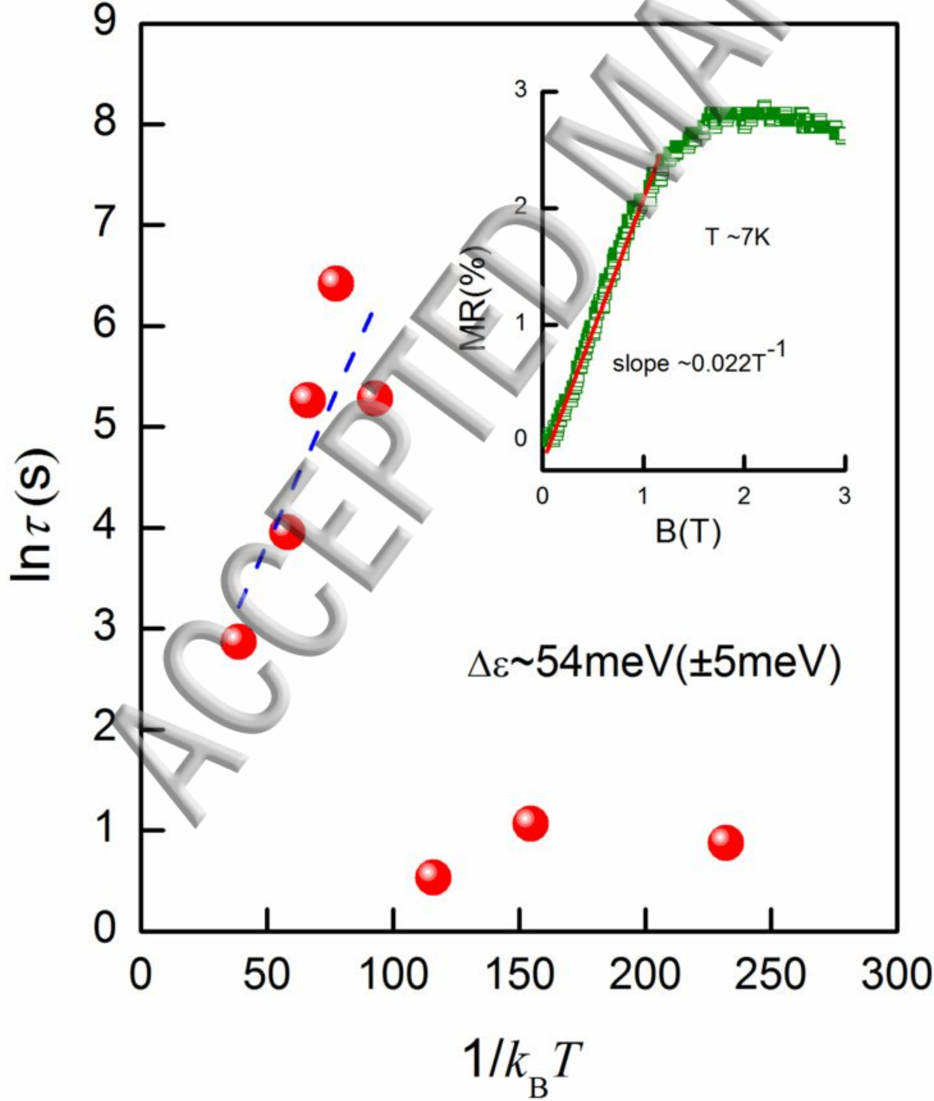
(a)
In contacts
$Pb_{1-x}Eu_xTe$
PbTe
$Pb_{1-x}Eu_xTe$
BaF_2
(b)
CB_b
CB_w
ΔE_C=295
E_{gb}=727
E_{gw}=190
VB_w
ΔE_V=242
VB_b
(c)
CB_b
ΔE_C=295
E_{L6}=219
E_{L5}=170
E_{O2}=154
E_{L4}=123
E_{L3}=78
E_{O1}=45
E_{L2}=38
E_{L1}=11
CB_w



(a)
σ /σ0
t(s)
10K
50K
75K
100K
125K
150K
175K
200K
300K
σM/σ0
T(K)
(b)
ρ (10^-1 Ω.cm)
T (K)
Off
On
dρ/dT(10^-3 Ω.cmK^-1)
T(K)
ACCEPTED MA



(a)
off
on
n(10^12cm^-2)
T(K)
10
1
0
50
100
150
200
250
300
350
(b)
Mobility (10^4cm^2/V.s)
1
0.1
T(K)
ACCEPTED MA



ln τ (s)
1/$k_B T$
Δε~54meV(±5meV)
MR(%)
B(T)
T ~7K
slope ~0.022T^{-1}