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# $R_0A$ product for PbS and PbSe abrupt $p$-$n$ junctions

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The effect is analysed of the concentration dopants on the $R_0A$ product of PbS and PbSe abrupt $p$-$n$ junctions. Calculations are performed for temperatures of 77, 200, and 300 K. The influences of the diffusion current (for radiative and Auger recombination), of the tunneling and depletion layer currents are considered.

## 1. Introduction

The investigations of the lead chalcogenide compounds started at date back to the early history of the semiconductor research. The first paper published on the subject appeared in 1874, when Braun reported asymmetrical nature of conduction between metal electrodes and the natural crystal of galena (lead sulphide) [1]. The wide application of lead sulphide in the early days of radio is well known. During World War II in Germany, next in the United States (Northwestern University) and in England (Admiralty Research Laboratory) the PbS, PbSe, and PbTe photoconductive infrared detectors having the polycrystalline thin film form were produced for the spectral range of 1.7 to 7 μm. These detectors have especially found military applications. Extensive reviews of the properties and applications of lead chalcogenides detectors are given in works [2, 3]*.

The photovoltaic detectors appeared to have a higher detectivity than photoconductive detectors within lower temperature range. The theoretical limited parameters of PbTe photovoltaic detectors were determined in papers [4, 5]. Also PbS and PbSe are used for production of photovoltaic detectors [6–8], the theoretical limiting parameters of these detectors are, however, not available.

In the present work the effect of the doping concentration on the zero bias junction resistance area product $R_0A$ is analyzed for abrupt $p$-$n$ junctions in PbS and PbSe.

## 2. $R_0A$ product for abrupt $p$-$n$ junction

The total dark current density flowing through the junction is given by

$$J = J_D + J_{GR} + J_T + J_L, \tag{1}$$

* In a recent paper ZIEP O. and MOCKER M., (Phys. Stat. Sol. (b) **98** (1980), 33) elaborated a modified theory of Anger recombination in lead chalcogenides.

where the particular components denote diffusion, generation-recombination in the depletion layer, tunneling and leakage current density, respectively. The latter may be due to bulk as well as to surface defects of the material. The value of $J_L$ cannot to calculated theoretically, but when a suitable diode technology and construction are used, the contribution of the $J_L$ component is negligible.

The $R_0A$ product determined by the diffusion current in the case of radiative recombination is [9]

$$(R_0A)_R = \frac{(kT)^{1/2}}{q^{3/2} n_i^2 \mu^{1/2} R^{1/2}} \sqrt{n_{ef}}, \tag{2}$$

where $n_{ef} = np/(n+2\sqrt{np}+p)$ is the effective doping concentration ($n_i$ and $p$ are the electron and hole majority carrier concentrations on both sides of the junction), $q$ is the electron charge, $\mu$ is the average value of the mobility of electrons and holes, $k$ is Bqltzmann's constant, $T$ is the temperature, $n_i$ is the intrinsic carrier concentration and $R$ is the coefficient of radiative recombination.

In the case of equal electron and hole masses $m_e^* \approx m_h^*$ the $R = R_n = R_p$ coefficient may be written in the form [10]

$$R = \frac{1 \times 10^{15} \bar{n} E_g^2}{(kT)^{3/2} K^{1/2} (2+1/K)^{3/2} (m^*/m_0)^{5/2}}, \tag{3}$$

where $\bar{n}$ is the refractive index, $E_g$ is the energy gap, $K = m_l^*/m_t^*$ is the effective mass anisotropy coefficient and $m_0$ is the mass of free electron. The $m^*$ can be determined if the longitudinal $m_l^*$ and transveral $m_t^*$ components of the effective mass are known, since $m^* = [1/3(2/m_t^* + 1/m_l^*]^{-1}$. In eq. (3) the values of $kT$ and $E_g$ should be expressed in electronovolts.

The intrinsic carries concentration is given by [11]

$$n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_{dn}^* m_{dp}^*)^{3/4} \exp\left[-\frac{E_g}{2kT}\right], \tag{4}$$

where $m_{dn}^*$ and $m_{dp}^*$ denote the density-of-states effective masses of electrons and holes, respectively. The formula (4) is valid for $E_g \gg kT$, being fulfilled in the case of lead chalcogenides. The values of density-of-states effective masses can be obtained from $m_d^* = N^{2/3}(m_l^* m_t^{*2})^{1/3}$, where $N = 4$ is the number of equivalent band extrema.

The $R_0A$ product determined by the diffusion current in the case of Auger recombination is [9]

$$(R_0A)_A = \frac{(kT)^{1/2}}{2q^{3/2} n_i^2 \mu^{1/2} C^{1/2}}, \tag{5}$$

where $C$ is the Auger recombination coefficient.

Due to the mirror symmetry of the conduction and valence bands $C = C_n$

$\cong C_p$. In the case of onevalley collision recombination ($K \approx 1$) [12]

$$C = \frac{1}{An_i^2}\left(\frac{kT}{E_g}\right)^{3/2} \exp\left[-\frac{3E_g}{2kT}\right], \tag{6}$$

where $A = (1; 5) \times 10^{-13}\ s$ for PbS and PbSe, respectively

The $R_0A$ product for abrupt $p$-$n$ junctions determined by depletion layer is given by the formula [13]

$$(R_0A)_{GR} = \frac{E_g^{1/2}\tau_0}{qn_i(2\varepsilon_s)^{1/2}}\sqrt{n'_{ef}}, \tag{7}$$

where $\varepsilon_s$ denotes the static dielectric constant and $n'_{ef} = np/(n+p)$ is the effective concentration. In the formula (7) $\tau_0$, i.e. the time determining the recombination by the Shockley-Read centres, is a parameter difficult to determine.

The $R_0A$ product determined by tunneling is given by [9]

$$(R_0A)_T = \frac{h^2\varepsilon_s^{1/2}}{2m_{tu}^{*\,1/2}q^3\sqrt{n'_{ef}}} \exp\left[\frac{8\pi m_{tu}^{1/2}E_g\varepsilon_s^{1/2}}{3qh\sqrt{n'_{ef}}}\right], \tag{8}$$

where $h$ is Planck's constant and $m_{tu}^* \approx m^*/2$ is the tunneling effective mass.

## 3. Numerical results of calculations and discussion

The dependence of the $R_0A$ product on the effective concentration of dopants at 77, 200, and 300 K was calculated using the formulae (2), (5), (7), and (8); the parameters are listed in table. The effective masses were determined basing

Table. Material parameters of PbS and PbSe

| | $T$ [K] | $E_g$ [eV] | $m_l^*/m_0$ | $m_t^*/m_0$ | $K$ | $\mu$ [m²/Vs] | $\bar{n}$ | $\varepsilon_s$ | $\varepsilon_\infty$ |
|---|---|---|---|---|---|---|---|---|---|
| PbS | 77 | 0.315 | 0.114 | 0.084 | 1.35 | 1.3 | 4.5 | 180 | 18.4 |
| | 200 | 0.373 | 0.135 | 0.099 | 1.35 | 0.15 | 4.4 | 180 | 17.6 |
| | 300 | 0.422 | 0.153 | 0.112 | 1.35 | 0.06 | 4.3 | 180 | 17.2 |
| PbSe | 77 | 0.175 | 0.081 | 0.043 | 1.9 | 1.5 | 5.2 | 250 | 25.2 |
| | 200 | 0.233 | 0.107 | 0.057 | 1.9 | 0.27 | 5.1 | 250 | 23.8 |
| | 300 | 0.282 | 0.130 | 0.070 | 1.9 | 0.10 | 5.0 | 250 | 22.8 |

on paper [14]. The effective masses of electrons and holes were expressed in their mean values; it has been assumed that the effective masses vary proportionally to the width of the energy gap. This approximation is justified by the results of the theoretical Kane model and experimental studies of the band structure of lead chalcogenide compounds [15]. The values of the energy gap $E_g$, effective mass anisotropy coefficients $K$, carrier mobilities $\mu$, refractive

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index $\bar{n}$, static dielectric constant $\varepsilon_s$, and of high frequency dielectric constant $\varepsilon_\infty$ were assumed after [15, 16].

It is expected that $\tau_0$ (see eq. (7)) depends on the temperature as well as the defect concentration. This dependence is not known for lead chalcogenides. In the calculations of $(R_0A)_{GR}$ it was assumed that $\tau_0 = 10^{-8}$s. The same order of time is often assumed for lead chalcogenides [13, 17].

The results of calculations are presented graphically in figs. 1–4 for 77,

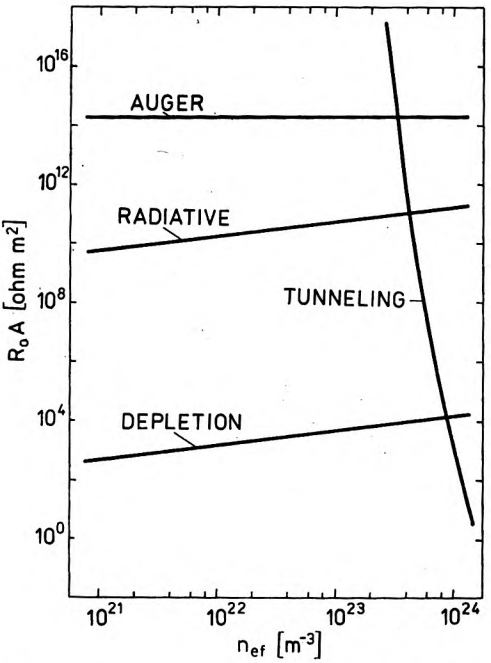


Fig. 1. The dependence of the zero bias resistance area product, $R_0A$, on the effective doping concentrations for abrupt PbS junctions at 77 K

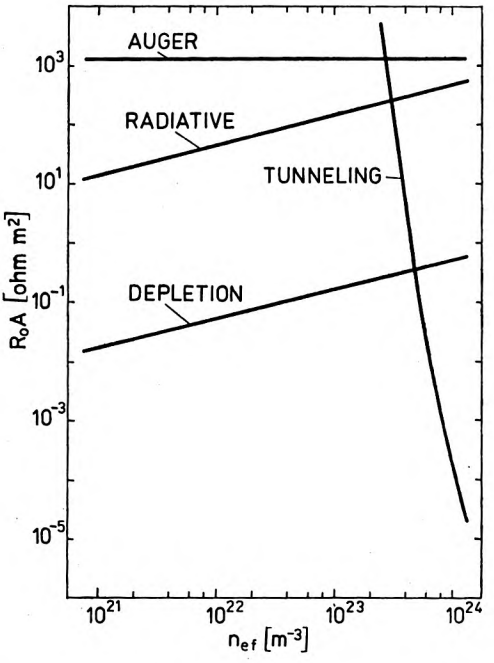


Fig. 2. The dependence of the zero bias resistance area product, $R_0A$, on the effective doping concentrations for abrupt PbSe junctions at 77 K. The experimental value is taken from paper [19] (○)

200, and 300 K. At 77 K the $R_0A$ product for PbS and PbSe abrupt $p$-$n$ junctions is determined by generation current of the depletion layer. For the radiative and Auger recombinations the theoretical estimates yield a few orders of magnitude larger values of the $R_0A$ product. The tunneling current produces an abrupt lowering of $R_0A$ at the effective doping concentrations of $8 \times 10^{23}$ m$^{-3}$ and $4 \times 10^{23}$ m$^{-3}$ for PbS and PbSe $p$-$n$ junctions, respectively. To obtain possibly high values of the zero bias resistance of the junctions the technological process of photovoltaic detectors preparation should be connected so that the concentrations of dopants be slightly below those concentrations. At such concentrations the influence of the Burstein-Moss shift is possible. The Fermi

level achieves the band edges at carrier concentrations of $(3.3, 1.4) \times 10^{23}$ m$^{-3}$ at 77 K, $(1.9, 1.0) \times 10^{24}$ m$^{-3}$ at 200 K and $(4.3, 2.7) \times 10^{24}$ m$^{-3}$ at 300 K for PbS and PbSe, respectively [18].

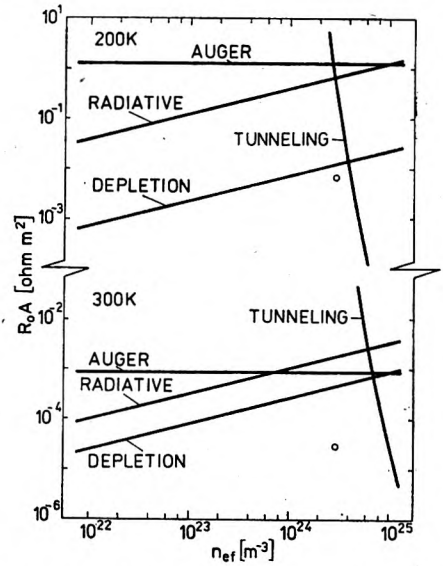


Fig. 3. The dependence of the zero bias resistance area product, $R_0A$, on the effective doping concentrations for abrupt PbS junctions at 200 and 300 K. The experimental values are taken from paper [6] (○)

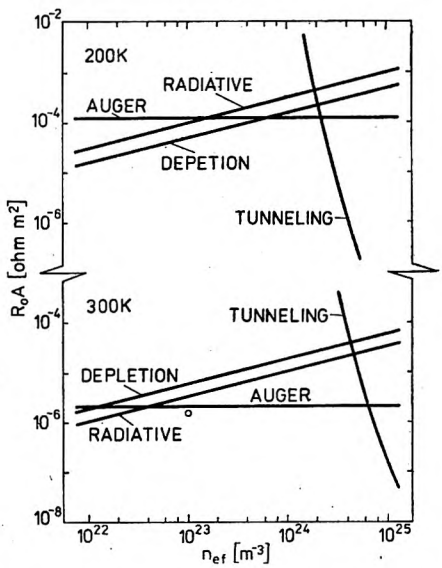


Fig. 4. The dependence of the zero bias resistance area product, $R_0A$, on the effective doping concentrations for abrupt PbSe junctions at 200 and 300 K. The experimental values are taken from paper [19] (○)

At 200 and 300 K the $R_0A$ product for PbS junctions is determined, as before, by generation-recombination current of the depletion layer.

At 200 K the effect of the depletion layer for PbSe junction is significant for $n_{ef} < 6 \times 10^{23}$ m$^{-3}$. In the range of higher dopant concentrations the effect of Auger recombination on the $R_0A$ product is revealed. At room temperature the Auger process is decisive for the value of the $R_0A$ product in a wide range of concentrations.

From figs. 1–4 it is apparent that the optimum effective doping concentrations (for which the $R_0A$ product takes the maximum value) increases with the temperature.

## 4. Conclusions

From the analysis of the effect of doping concentrations at both sides of the abrupt $p$-$n$ junction in PbS and PbSe on the value of the $R_0A$ product it follows that at liquid nitrogen temperature the generation-recombination current within the junction depletion layer plays a dominant role. A further increase of the $R_0A$ product can be achieved by increasing the time $\tau_0$ see (eq. (7)), which, in turn, is limited by the technology process used in junction fabri-

cation. The diffusion processes appears to be important at the range of higher temperatures.

It is difficult to compare results of theoretical calculations with experimental data (known from publications), since in the experimental works the doping concentrations at the both sides of the junction are not given and the junction profile is not always described (the abrupt junctions are considered in this work). Figs. 2–4 show the experimental values from only two papers: for linearly graded PbS junction [7] and for PbSe junction [19]. In the latter the PbSe junction profile was not found [19]. A rough comparison between the calculated and experimental data [6, 19] shows that the construction of higher quality *p-n* junctions seems to be possible, especially for PbSe at lower temperature.

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## Произведение $R_0A$ скачкообразных *p-n* переходов PbS и PbSe

В работе анализируется влияние уровня концентрации примесей на произведение $R_9A$ скачкообрабаых *p-n* переходов, изготовленных в PbS и PbSe. Расчёты произведены для температуры 77, 200 и 300 K. Рассмотрено влияние диффузионного (для излучательной рекомбинации и рекомбинации Оже), туннельного и генерационно-рекомбенационного тока перехода.