PHYSICS OF SEMICONDUCTORS AND DIELECTRICS

ELECTRON–POSITRON ANNIHILATION IN THE
NARROW-BAND SEMICONDUCTOR $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$

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Positron annihilation processes in mercury–cadmium–telluride semiconductor compounds have been studied. Calculations of the positron thermalization time, the bulk annihilation rate, and the positron capture rate for the simplest crystal lattice structural defects have been carried out. The annihilation properties of materials containing growth defects and defects induced by high-energy particles have been determined experimentally. The profiles of vacancy-type defects formed during ion implantation were determined using slow positrons. The positron annihilation data are compared with the results of electrophysical measurements.

Cadmium–mercury–tellurium (CMT) semiconductor compounds of are the basic material of infrared optoelectronics. For realization of the potential advantages of this material it is necessary to carry out a complex investigation of the properties of the defects which in the final reckoning determine its electrophysical and recombination properties. During the growth of a narrow-band CMT solid solution and subsequent defect-forming actions during the creation of device structures based on it various kinds of defects such as impurity atoms, dislocations, block boundaries, second-phase inclusions, amorphous and disordered layers are introduced. Their effects on the material parameters are primarily connected with the presence of vacancy defects, whose observation and identification presents substantial difficulty using traditional methods. At the same time a unique possibility for investigating the vacancy defects arises from the phenomenon of positron annihilation in a material, which allows one to obtain information about its electronic structure.

The present work is devoted to the study of electron–positron annihilation in CMT both computationally and experimentally. Here as the object of investigation we used materials with grown defects and defects induced by high-energy irradiation (electrons, ions, protons, gamma rays, and x-rays). Great attention is given to the use of electron–positron annihilation methods based on detection of the angular distribution spectrum of annihilation photons and also the lifetime spectrum of the positrons. Examples of the use of slow positrons for defect diagnostics are given. Physical justification of the data obtained is carried out by comparison with the results for other methods.

1. CALCULATION OF THE POSITRON THERMALIZATION TIME

One of the main prerequisites for using the positron annihilation method to study solid structures is the fact that the high-energy positrons emitted by radioactive sources rapidly lose their energy after entering the sample under study and are slowed to thermal velocities (thermalized) after a time much less than their annihilation lifetime. Because of thermalization the kinetic energy of the positrons at the instant of annihilation is negligibly small in comparison to the electron energies. Thus the parameters of the annihilation photons carry information about the electronic structure of the material studied.

The positron thermalization problem in metals was solved by the calculations of Lee-Whiting [1] who showed that in metals the thermalization time for positrons due to excitation of the electron subsystem is $\sim 10^{-12}$ sec. This value is two orders of magnitude less than the average positron lifetime in metals. In semiconductors the loss of positron energy due to the
Fig. 1. Dependence of the fraction of positrons captured by defects on the defect concentration: 1) divacancies ($N_d$); 2) doubly-charged vacancies; 3) dislocations ($N_d$).

Fig. 2. Dependence of the intensity of the long-lived component of the lifetime spectrum and the Doppler broadening parameter of the annihilation line in CMT on the vacancy concentration.

excitation of electrons is limited by the energy which corresponds to the forbidden band width. These processes play the main role for the slowing of a positron from an initial kinetic energy $E_0 = E_g$ which occurs after a time $\sim 10^{-12}$ sec. After this the main role in the slowing of a positron is played by the processes of its interaction with lattice vibrations [2].

In agreement with [3] the rate of positron energy loss due to phonon emission can be described by the equation

$$\frac{dE_\perp}{dt} = c E_\perp^2.$$  (1)

The constant $c$ from Eq. (1) within the framework of the deformation potential model takes the form [4]

$$c = m_*^p E_1 / \sqrt{2 \hbar^2 \rho},$$  (2)

where $m_*^p$ is the positron effective mass, $\rho$ is the density of the material, $\hbar$ is Planck’s constant, and $E_1$ is the deformation potential constant.

Integration of Eq. (1) taking account of the conditions

$$E_\perp(t_0) = E_g, \quad E_\perp(t_r) = \kappa T,$$

where $T$ is the temperature of the crystal and $\kappa$ is Boltzmann’s constant, gives

$$t_r - t_0 = \left[ (\kappa T)^{-1/2} - E_g^{-1/2} \right]/c.$$  (3)

In Eq. (3) $t_0$ is the time after which the positron energy decreases from $E_0$ to $E_g$, and $t_r$ is the total time for positron thermalization. The calculations show that the thermalization time of a positron in Hg$_{1-x}$Cd$_x$Te solid solutions is practically independent on the composition (through $E_g(x,T)$) and depends weakly on the crystal temperature. At 300 K, $t_r = 10$ psec, while at 77 K, $t_r = 20$ psec. These values are 2-3 times larger than found in [4] for Ge and Si.

In order to fully solve the problem of positron thermalization in CMT it is necessary to know yet another parameter – the positron annihilation lifetime.

In agreement with Brandt’s [5] capture model the minimum positron lifetime in a crystal due to positron annihilation in bulk material and is $\tau_{\min} = \tau_0 = 1/\lambda_0$ where $\lambda_0$ is the bulk annihilation rate. Analysis of the behavior of positrons in a semiconductor which contains a uniform electron gas with a forbidden band width $E_g$ done by the authors of [6] allows one to find the following expression for the bulk annihilation rate: