Positron annihilation in polyelectron system of strong spin-orbit field induced by bismuth impurity centers in natural silicon

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In silicon to be characterized by a low spin-orbit interaction, a heavy and oversized atom of bismuth impurity creates strong spin-orbit field which allows one to increase both the efficiency of spin polarization of charge carriers and energy of storing of information in the process of quantum computing. The tuning of qubit-forming Bi impurity centers of different symmetry is a challenging problem in manipulating the spin interactions. Meanwhile, a data on local electron properties of the crystal lattice, to be usually obtained with the positron probing, are lacking for Bi impurity centers. Having applied PALS and Hall effect measurements, for the first time we have observed a decrease of probability of 2γ–annihilation with the increase of number of electrons contacting positron at the bismuth impurity centers having both T_d and D_{3d} symmetry.

The transition of electrons from the conduction band to the donor ground state $E\{Bi\} = E_c - 0.069$ eV in the polyelectron system of Bi impurity center having T_d symmetry has been accompanied by an increase of the lifetime of e^+e^- pairs regarding 2γ–annihilation.

Enormously large cross-section of localization of positron is estimated to be equal to ~ (1.3–1.7) $\times 10^{-13}$ cm^2 with the growth of occupancy of the donor level, Δn_e [E{Bi}] ~ $1.2 \cdot 10^{16}$ cm^{-3}, with decreasing temperature from 295 to ~ 25 K. Involvement of ^{29}Si atom(s) tied to ^{209}Bi one in the impurity center influences markedly on 2γ–annihilation of a localized positron. The averaged over temperature the probability of 2γ–decay per unit time becomes larger by a factor of Δ~2.18 compared to the value $\Gamma=(2.09\pm0.09)\times10^9$ s^{-1} known for the isolated polyelectron ($e^-e^+e^-$) [1]. The picture looks as if the admixture of the charge-even states of e^+e^- pairs to the polyelectron in the spin-orbit field of Bi impurity center would decrease probability of its long-lived 2γ–decay, whereas the charge-odd states of e^+e^- pairs inhibit the contribution of short-lived component of the singlet e^+e^- pairs to the resulting probability of 2γ–annihilation.

Owing to trapping a vacancy, Bi donor center changes its symmetry to D_{3d} after irradiation of material with 15 MeV protons. The Bi atom saturates its valency, increases the number of bonds in the vacancy–Bi–atom pair (V–Bi), and the factor Δ decreases its value by ~10–11%. The V–Bi pair is a deep donor that is seen from the data of electrical measurements in the course of isochronal annealing. Also, the polyelectron system formed in the spin-orbit field of V–Bi pair is thermally stable up to ~350 °C. Then the probability of 2γ–decay, Δ×Γ, begins restoring its value, and the Bi impurity center acquires T_d symmetry during a rather short annealing stage ranging temperatures 370 to ~430 °C. The effects observed are discussed in the light of current reconsidering of a whole conception of formation of the vacancy-phosphorus centers that trap positrons and are characterized by weak spin-orbit interaction in silicon [2-4].

References

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