Size difference of anisotropic muonium relaxation rates in *n*- and *p*-type semiconductors

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The reported dramatic size difference of the anisotropic muonium (Mu*) relaxation rates in *n*- and *p*-type silicon is explained on the basis of the difference in cross section between e^--H and e^+-H scatterings with experimental evidence of corresponding impurity scatterings in semiconductors.

Muonium states in solids, especially in semiconducting materials like Ge, Si, or GaAs, are drawing attention from the viewpoints of both spectroscopy and dynamics.[1] Muonium is noted for its similarity with hydrogen atom. It is stressed that muonium defect centers are even better observed than hydrogen centers.[2] A strong relationship of the muonium with the background semiconductor particularly shows up in doped materials. Weidinger *et al.*[3] have observed that, in *n*-type Si, the relaxation rate of the isotropic muonium, λ, increases with carrier density. Albert, Möslang, Recknagel, and Weidinger[4] have similarly studied the relaxation rate of the anisotropic muonium, λ^*, both for *n*-type and *p*-type Si. The latter authors, in particular, write down the doping-dependent contribution in crude closed forms, namely,

$$\lambda^* = 2\times 10^{-7} n \text{ cm}^3\text{s}^{-1} \ (n\text{-type}),$$
and (1)
$$\lambda^* = 2\times 10^{-9} n \text{ cm}^3\text{s}^{-1} \ (p\text{-type}),$$

where n is the carrier density.

We note in Eq. (1) a two-order-of-magnitude difference in λ^* (doping) between *n*- and *p*-type Si. The authors give no explanation for such a large difference. The purpose of this paper is to make a proper mention of this point.

Muonium, in its structure, is almost a duplicate of hydrogen atom because of the heavy mass of the muon. Hence its interaction with free carriers, electrons and holes, can be simulated with e^--H or e^+-H interaction. The rest of the argument will always be based on this ansatz.

The free-carrier associated relaxation rate of muonium can be considered proportional to the muonium-free carrier collision rate,

$$\nu = \sigma v_c n, \quad (2)$$

where σ is the collision cross section, v_c is the thermal velocity of the relevant free carriers in the semiconductor, and n the density of the free carriers. If we make a comparison between *n*- and *p*-type materials, we are implicitly assuming the same carrier density. As for the thermal velocity, we have to take account of the difference in effective mass between electron and hole. The density-of-states effective mass for conduction electrons in Si is approximately $0.3m_0$. The same for holes can roughly be equated with the heavy-hole mass, $\sim 0.5m_0$. Thus one expects $v_e \sim 1.3v_h$, where v_e and v_h are electron and hole velocities, respectively. However, such a big difference as observed in Eq. (1) cannot be accounted for by the carrier-thermal-velocity argument. The essential factor responsible for the difference should consist in the collision cross section. We may look at the difference in cross section between e^--H and e^+-H scatterings. A reliable variational calculation is available for e^--H and e^+-H scattering cross sections.[5] Its result has been applied to semiconductor physics to account for the electron scattering by neutral impurities.[6-8] A neutral pentavalent donor in Ge or Si is compared to a hydrogen atom while a neutral trivalent acceptor to an antihydrogen atom. Thus, the electron–neutral-donor scattering can be simulated by e^--H scattering, while the electron-neutral acceptor scattering by e^+-H scattering, if every charge involved is

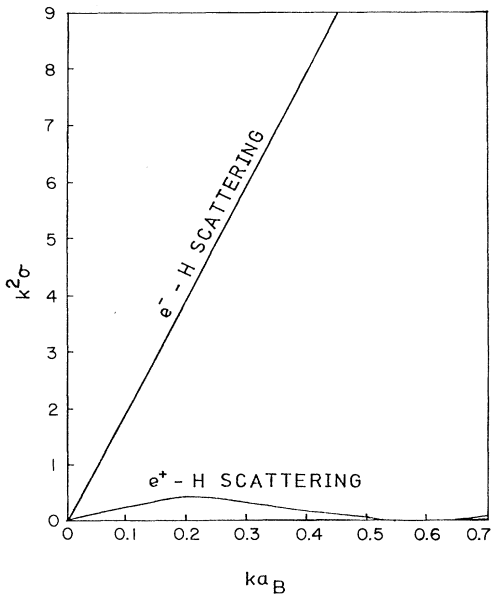

FIG. 1. Cross section σ (multiplied by k^2) against the incident particle wave number k (multiplied by the Bohr radius a_B) for electron–hydrogen-atom and positron–hydrogen-atom scatterings. The solid lines are drawn based on the calculation by Schwartz (Ref. 4).

the inverse of its sign.

As a guide, the cross sections of the relevant atomic scattering are shown in Fig. 1 against the wave number of the incident particle. Nearly an order of magnitude difference in size between e^--H and e^+-H scattering cross sections exists at low wave numbers. The difference is enhanced at high wave numbers of the incident particle. In semiconductors, the ratio $\sigma_{e\text{-}D}/\sigma_{e\text{-}A}$ obtained at 4.2 K is ~ 10 in Ge and ~ 40 in Si,[8] where $\sigma_{e\text{-}D}$ and $\sigma_{e\text{-}A}$ stand for cross sections of electron–neutral-donor and electron–neutral-acceptor scatterings, respectively. Comparison of the cross section in the case of muonium scattering is usually made at higher temperatures, 40–140 K, so that the observed difference by a factor of 10^2 would not be too surprising.

It is true that one may not entirely paraphrase the muonium and impurity scatterings in semiconductors. In the case of impurity scattering, we change the target from donor to acceptor and the incident particle is an electron, while in muonium scattering the target is unchanged and the incident particle is changed from electron to hole. An impurity in the semiconductor is immobile, while muonium could be mobile. The muonium state with which we have seen a difference in carrier scattering between *n*- and *p*-type Si is anisotropic, or Mu*. For direct comparison with impurity states in a semiconductor, or more directly with the proper $e^{\pm}$-H scatterings, one might argue that the isotropic Mu state is more appropriate. The Mu state experiments so far, however, report a much less dramatic difference between *n*- and *p*-type materials and sublinear dependence on carrier concentration.[9,10] These observations are considered to indicate the Mu trapping at the impurity sites.[1] A somewhat similar situation in semiconductors—electron scattering by exciton bound at impurity—entirely changes the scattering aspect either from electron-impurity or from electron-exciton collision.[11,12] Carrier scattering by muonium-impurity complex thus casts a new problem. Electron scattering by muonium-donor complex and hole scattering by muonium-acceptor complex will have to be studied very carefully to account for the reported Mu case in *n*- and *p*-type Si.

With all these yet unsettled, the essential feature of the close similarity between *e*,*h*-Mu* and *e*-*D*,*A* scatterings, in the present author's opinion, is justified and reflected in the difference of λ^* between *n*- and *p*-type semiconductors.

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