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Measurement of the near-threshold Auger ionization probability in silicon

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Abstract. A new method of investigation of the Auger ionization probability, based on the analysis of the static characteristics of a tunnel MIS emitter Auger transistor, is proposed. The main advantages of this method are monoenergetic electron injection and very simple energy control. The ionization probability (quantum yield) for silicon was first determined as a function of electron energy E_e in the near-threshold range. The Auger effect in Si is noticeable even for $E_e \simeq 1.2$–1.5 eV. The data obtained in the present paper are in good agreement with some experimental and theoretical results published for $E_e > 2$ eV.

1. Introduction

In the last two decades a great deal of work has been done on the investigation of the Auger ionization probability for Si in the range of relatively low electron energies [1–6]. The latest results, primarily theoretical but some experimental too, are presented together in figure 1, which clearly shows that our knowledge of the ionization probability is very far from perfect. Indeed the discrepancy in quantum yield (averaged number of electron–hole pairs produced by one initial electron) predicted by different workers reaches two orders of magnitude or more, especially just near E_g. On the other hand, the range $E_e < 2$ eV is of critical importance from a practical point of view. There is no doubt that this problem deserves further study, the more so as no experimental data were obtained in this range, because of the absence of appropriate methods of measurement.

Below, we set forth a new method of near-threshold Auger ionization investigation† based on the analysis of the static characteristics of the tunnel MIS emitted Auger transistor‡ (figure 2(a)). In this device, hot electrons are injected into the Si bulk from a metal emitter and, in some operation modes, they may cause Auger ionization. The Auger effect may be quantitatively determined by measurement of the terminal currents.

An important advantage of such a transistor as a basic device for investigation of the ionization process is that the injected electrons are almost monoenergetic (the energy distribution of these electrons is a multiple of the tunnelling probability, which increases dramatically with increasing energy and the Fermi function in the metal which decreases

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† Auger ionization is similar to the impact ionization process except that the excess kinetic energy occurs through the potential step of injection instead of drift in electric field.

‡ Several years ago, Chang *et al* [5] tried to use a similar structure for the investigation of the ionization process in Si, but their samples were fabricated on relatively highly doped substrates (figure 2(c)). Such devices do not demonstrate transistor characteristics and the interrelation between V_{be} and the electron energy is much more complicated.

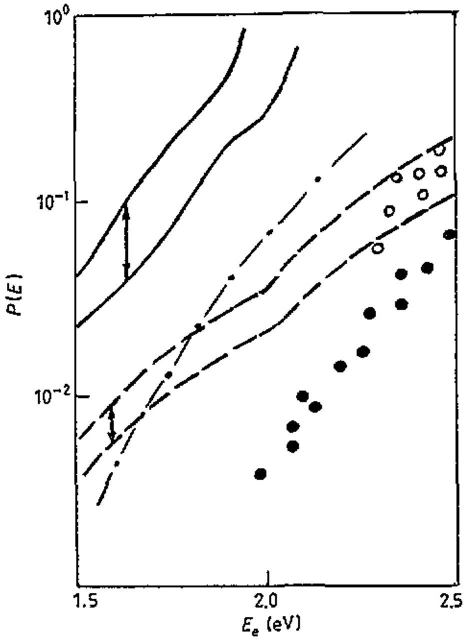

Figure 1. Quantum yield of Auger ionization as a function of electron energy E_e: ——, theoretical results [1]; - - - -, theoretical results [2]; — · —, theoretical results [3]; ●, experimental data [4]; ○, experimental data [5]. No experimental data were obtained for $E_e \ll 2$ eV. (From [6].)

at $E_e > E_{Fm}$; see figure 2(*b*). In addition, the energy of the electrons can be simply controlled by measurement of the base-to-emitter bias V_{be}. (Energy control is often a very serious problem in investigating the ionization probability.)

In general, the method proposed below is the following. We use the analytical model of the Auger transistor to calculate the quantum yield of Auger ionization on the basis of the measured dependences of terminal currents on the base bias. Some adjustable parameters required for our model may be experimentally found in operation modes without Auger ionization.

2. Theory of the method

Figure 2(*b*) represents the energy band diagram of the studied transistor fabricated on the basis of an Al/tunnel SiO_2/n^--Si structure. A high insulator voltage is provided almost totally by the charge of the inversion layer (the contribution of the depletion layer is small). The holes lost because of leakage into the metal are resupplied by the external base electrode (adjacent positively biased p^+–n^- junction). At some insulator bias, hot electrons injected through the insulator become capable of Auger ionization. When the insulator bias increases further, the current originating from the Auger ionization plays an essential role in the balance of currents flowing through the transistor. The energy of electrons may be significantly varied using V_{be} in the most interesting range (from 0 to 2.5–3 eV [7]).

For true Auger ionization measurements, it is necessary that the ionization occurs in a sufficiently low electric field. In our case the experimental conditions meet this requirement

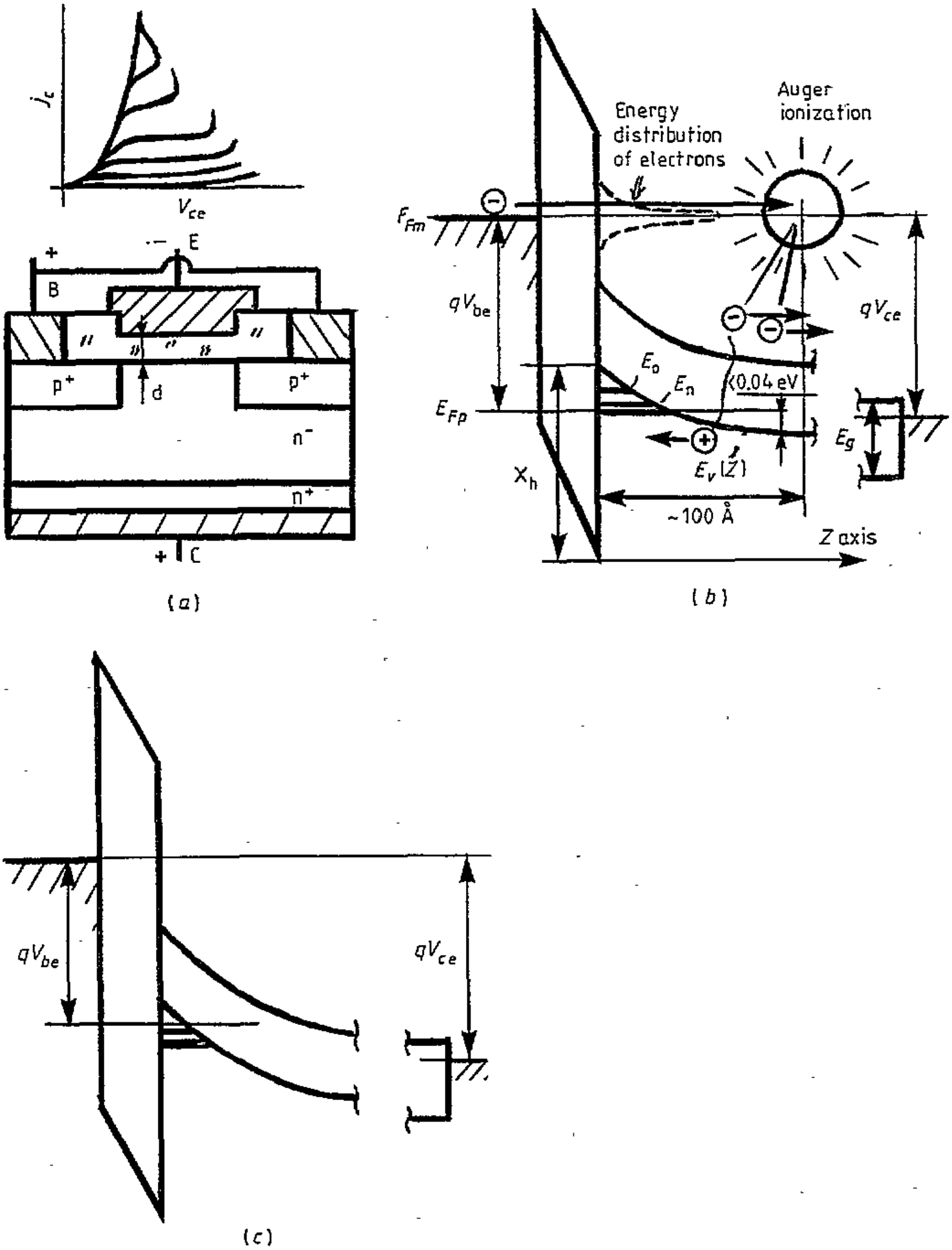

Figure 2. (*a*) The structure of the tunnel MIS emitter Auger transistor used in the experiments and a typical family of its common emitter characteristics (each curve corresponds to a particular base current density). B, base; E, emitter; C, collector. (*b*) The energy band diagram of the Auger transistor. Injected electrons are almost monoenergetic. After passing through the inversion layer, they appear in the low-field region (if the collector doping is low). $E_v(z)$ is the valence band edge at the plane z. (*c*) The energy band diagram of the tunnel MIS structure fabricated on a heavily doped n-Si substrate. This structure in less convenient for Auger ionization measurements. The electric field in the depletion layer is high and, unlike the device shown in (*b*), the relation between E_e and V_{be} cannot be given by equation (1).

since the electric field is high only in the inversion layer just near the interface. Auger ionization occurs primarily behind this area because a typical ionization length is about 10 nm [8], which is at least several times more than the width of the inversion layer. As follows from the analysis of the energy band diagram, if the substrate doping density is rather low (10^{14} cm^{-3} or less) and the base-to-collector voltage is small ($V_{bc} < 2$ V), the band bending in Si has already become insignificant at a distance of 3–4 nm from the SiO_2–Si interface. The Fermi quasi-level for holes remains very close to the valence band edge, after their intersection, and the value of $E_{Fp} - E_v(z)$ never exceeds 0.01–0.03 eV at 5–20 nm into the bulk of Si under high-insulator-bias conditions. Therefore the electron energy is given by

$$E_e = qV_{bc} - E_g. \tag{1}$$

In many papers (see, e.g., [9, 10]) it has been pointed out that the values of the electron (and hole) effective mass in insulator and barrier heights known for MIS structures with a thick insulator layer cannot be used in tunnel studies. So we take these values as adjustable parameters.

It is evident that no Auger ionization events are possible if $E_e < E_g$. For V_{be} corresponding to $E_e < E_g$ we measure the base current as a function of the base-to-emitter voltage (figure 3) and, using these data, calculate the above-mentioned adjustable parameters of the tunnel barrier for holes. After they are determined (we have assumed that holes are only lost by tunnel leakage), we can analytically predict the value of hole leakage current density j_L as a function of the base bias for a wide range of V_{be}. Then the difference between j_L and measured base current density at $E_e > E_g$ is attributed to the Auger ionization current density so that the latter can be found as

$$j_a = j_L(V_{be}) - j_b(V_{be}). \tag{2}$$

Of course, to use (2), we must be sure that the hole diffusion current density j_D into the collector bulk does not play an essential role. During our experiments we choose V_{ce} to be slightly higher than V_{be}, since under such conditions $j_D = 0$ [11, 12].

An important point in our model of the structure is that we take into account the quantization of hole motion in the direction transverse to the interface plane, which is commonly ignored in theoretical analyses of the tunnel MIS emitter transistor [9, 12].

The equation for the hole tunnel current density flowing from the inversion layer is

$$j_L = \sum_n q\frac{E_n}{h}N_n\theta(E_n) \tag{3}$$

where E_n is the energy of the bottom of the nth subband, E_0 being the ground state, N_n is the hole concentration in the nth subband, θ is the tunnelling probability and h is Planck's constant. An analogous equation has been used in [13].

If the insulator bias is high, almost all the holes occupy the two lowest subbands and, to simplify the analysis, we ignore all the terms in (3) except the first two. It has been checked that the contribution of the holes from the other subband towards the hole current density is very small, especially for the (111) surface. The energies E_n and the occupancies of subbands can be calculated as if there was no leakage [14] (see also [13]).

The tunnelling probability is

$$\theta(E) = \exp\left(\frac{4\sqrt{2m_h}}{3hqF_{in}}2\pi((\chi_h - E)^{3/2} - (\chi_h - E - qdF_{in})^{3/2})\right) \tag{4}$$

where F_{in} is the electric field in SiO_2, χ_h is the valence band discontinuity at Si–SiO_2 and d is the SiO_2 thickness.

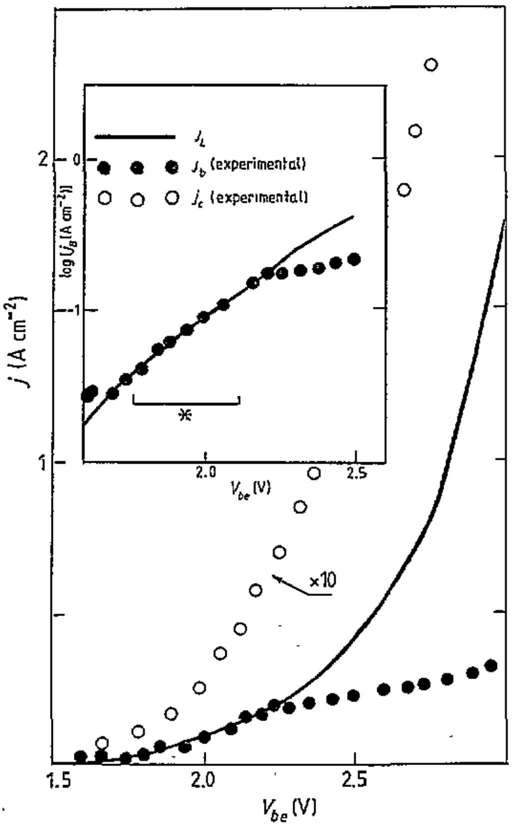

Figure 3. Experimental dependences of the collector and base current densities on the base bias (for one of the devices used for calculation of the quantum yield), where the collector voltage is 4 V: ——, leakage current computed with such parameters as to provide the best fit to experimental data; *, approximation range. For details see text.

To determine the fitting parameters m_h and χ_h, we should preliminarily select the range of base-to-emitter voltages for approximation. It is not worth extending this range down to small V_{be}, because under small V_{be} the other ways of losing holes, such as recombination, may be important. In addition, the assumption that the holes occupy only the lowest subband is intolerable under such conditions. These factors are difficult to take into account. Experience has shown that the best range for approximation is somewhere between $V_{be} = 1.7$ and 2.15 V. In this case the values obtained for m_h and χ_h, are almost insensitive to the narrowing of the approximation range inside this range.

Most of our measurements were performed using devices with a SiO_2 layer 2.5 nm thick. The values of χ_h found from the approximation were usually about 3.5–4.0 eV and m_h is about 0.2. With increase in the insulator thickness χ_h. m_h markedly increased, becoming close to the values known for 'thick' structures, as should have been expected.

The criterion used for the approximation is minimization of the sum of relative logarithmic errors in experimental points. The motivation for using such a criterion is roughly the exponential dependence of the base current on the base bias measured earlier [11] in similar structures,

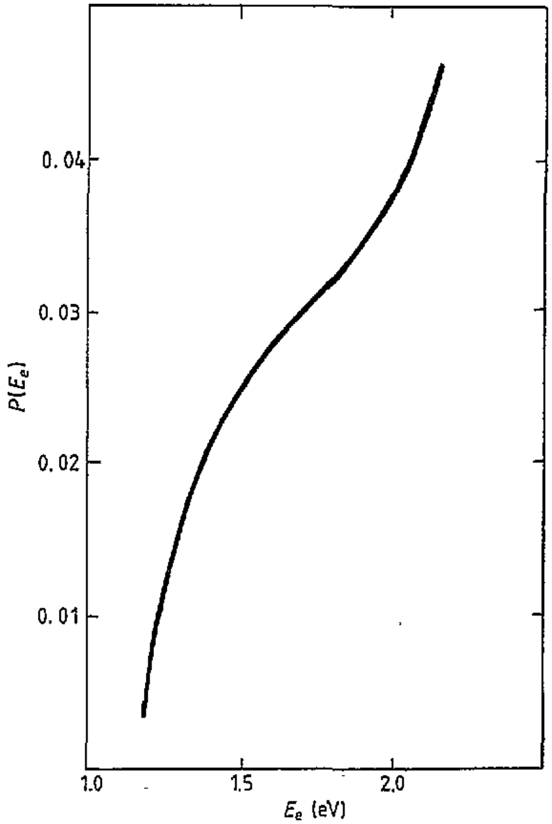

Figure 4. Quantum yield (Auger ionization probability or averaged number of electron-hole pairs produced by one initial electron) as a function of electron energy for Si(100) at 300 K.

3. Experimental results

The results obtained in study of our samples are presented in figure 4. The value of the Auger ionization probability (quantum yield) was calculated as

$$P(E_e) = \frac{j_a}{j_c - j_a} \tag{5}$$

where j_c is the measured collector current density.

An important fact is that there were no changes in the transistors' characteristics during measurements. In principle, some changes in tunnelling characteristics could occur due to trapping of carriers in the oxide and we have indeed observed the effect of trapping in the structures with a thicker insulator (e.g. 5–7 nm). The absence of any degradation of the 2–3 nm oxide at least for 1–2 h (which is quite sufficient to perform the measurements) arises probably from the difference in charge transport mechanisms through the thin tunnel and thicker SiO_2 layers.

As far as we know, the results shown in figure 4 are the first experimental data on the Auger ionization probability for the near-threshold range. As was first suggested in [15], $P(E_e)$ has a segment which rises fairly rapidly just near the threshold and then slightly slows down. Even at $E_e \simeq 1.4$–1.6 eV the ionization probability for Si is not negligibly small, as predicted in earlier work [8]. In the range $E_e \simeq 2.2$ eV our results are in satisfactory agreement with the experimental data of [5] and for $E_e \simeq 1.6$–2.0 eV (where no experimental data were obtained previously) with the theoretically predicted curve [2] (broken curve in figure 1).

The difference between the results for $P(E_e)$ obtained with different samples was no more than 25%.

The conclusions which may be drawn from this work are the following. First, a new method of Auger ionization measurements is proposed for the near-threshold range with such important advantages as monoenergetic electron injection and very simple energy control. Secondly, the Auger ionization probability in Si was found to be significant even in the low-energy range.

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