Extended Abstracts of the 1992 International Conference on Solid State Devices and Materials, Tsukuba, 1992, pp. 73-75

B-2-6

Local Zener Phenomenon—A Mechanism of p-n Junction Leakage Current—

Kiyonori Ohyu and Atsushi Hiraiwa
Central Research Laboratory, Hitachi Ltd.,
Kokubunji, Tokyo 185, Japan

The origin of the extremely large p-n junction leakage current which is due neither to generation-recombination current nor diffusion current is investigated. It is shown to be due to the local Zener effect, induced by the local enhancement of the electric field around precipitates in the depletion layer. A new approach to suppress this Zener effect by controlling the profile of the electric field is also proposed.

§ 1. Introduction

As the integration scale of LSIs increases, degradation of device characteristics due to p-n junction leakage is becoming a serious problem. The refresh operation failure in DRAM cells due to extremely large leakage current is one typical example. Such leakage is not always explained by generation-recombination current or diffusion current. It has been considered that this may be caused by a crystalline defect[1] or chemical contamination[2] introduced during the device manufacturing process. However, the mechanism has yet to be reported in detail. In this study, we investigated the mechanism of this extremely large leakage current and confirmed that they are caused by the local Zener effect due to precipitates in the depletion layer, as predicted earlier by Goetzberger and Shockley[3]. Furthermore, an approach to suppress this effect by controlling the profile of the electric field is also proposed.

§ 2. Experimental

Junction diodes investigated in the present study were fabricated as follows: Device isolation areas were formed using the conventional LOCOS method on CZ (100) p-type 1Ω−cm Si substrate. A p-type channel stopping layer with a B concentration of about $1\times10^{17}/cm^3$ was formed just beneath the LOCOS oxide film. N^+/p junctions were formed by As implantation (25keV, $2\times10^{15}/cm^2$) followed by N_2 annealing (900°C, 30 min). Finally, the surface passivation by a thick PSG film, and Al wiring were followed by sintering heat treatment at 450°C in H_2.

§ 3. Results and Discussion

Typical reverse I-V characteristics of both normal and degraded junctions which is an issue of this study are shown in Fig. 1. Leakage of the degraded junction increases more rapidly with reverse bias than that of the normal junction.

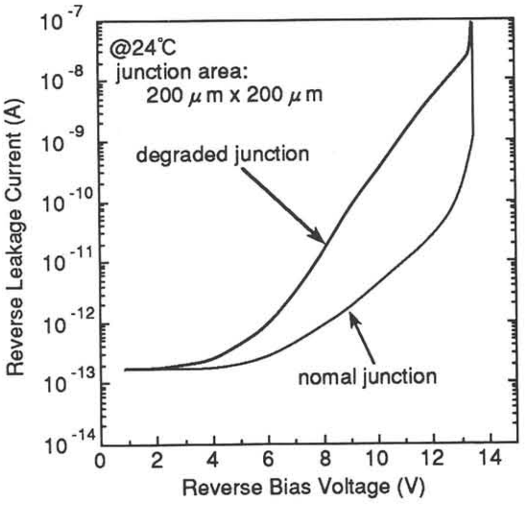

Fig. 1 Reverse leakage current of n+/p junction.

To determine the location of the source and the mechanism which produce this leakage, temperature dependence was measured for both area and peripheral components (Fig. 2). The theoretically obtained temperature dependence of both generation-recombination (g-r) current (activation energy: Ea=0.55eV) and diffusion current (Ea=1.1eV) are also shown in the figure. From the figure, we can conclude that, (1) peripheral components of both junctions behave identically, which means that the area component is responsible for junction degradation; (2) the area component of the degraded junction is due to neither g-r current nor diffusion current; and (3) the area component of the degraded junction shows small temperature dependence. Together, these indicate that the origin of degraded junction leakage can only be explained by an electric field increase within the depletion layer.

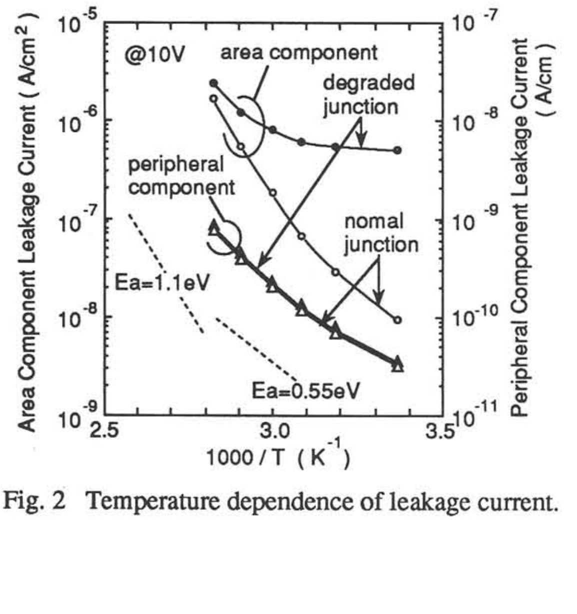

Fig. 2 Temperature dependence of leakage current.

To investigate the origin of the leakage further, the local enhancement of the electric field around small precipitates is considered. In obtaining the local electric field analytically, we assume that a spherical precipitate exists in a uniform electric field. Strictly speaking, the electric field in the depletion layer is a function of depth and is not uniform. However, the width of the electric field enhancement is as small as the radius of the precipitate (R) as shown later. Thus a uniform electric field can be assumed when the precipitate is very small relative to the depletion layer width. The theoretical field enhancement coefficient (η) at the location expressed by polar coordinates (r,θ) with the origin at the center of the precipitate is obtained by the following equation[4]:

$$\eta^2 = (1+2A/r^3)^2 - (3A/r^3)(2+A/r^3)\sin 2\theta$$

where

$$A = R^3(\varepsilon_i-\varepsilon_o)/(\varepsilon_i+2\varepsilon_o),$$

ε_i and ε_o are the dielectric constants of Si and the precipitate, respectively. Thus, the maximum coefficients at r=R are obtained as:

$$\eta(\max) = 3\varepsilon_i/(\varepsilon_i+2\varepsilon_o) \quad \varepsilon_i > \varepsilon_o \ (\theta=0)$$
$$= 3\varepsilon_o/(\varepsilon_i+2\varepsilon_o) \quad \varepsilon_i < \varepsilon_o \ (\theta=\pi/2)$$

Calculated results are shown in Figs. 3 and 4. As can be seen from the figures, the $\eta(\max)$ for SiO_2 and metal precipitates are about 1.3 and 3, respectively, and this enhancement extends only as far as the radius of the precipitate.

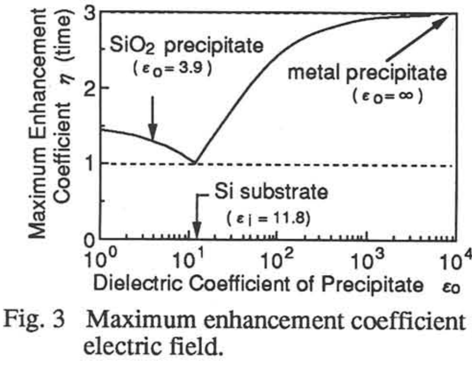

Fig. 3 Maximum enhancement coefficient of electric field.

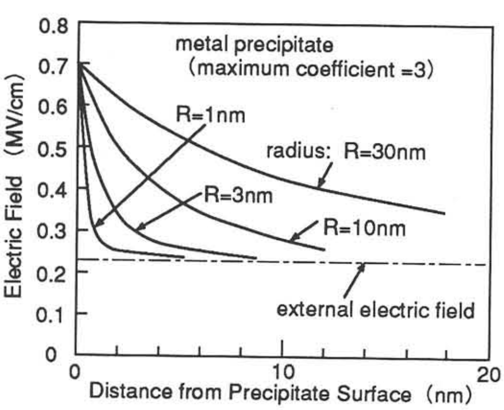

Fig. 4 Profile of electric field around precipitate.

Leakage current under a high electric field can be attributed to the avalanche or Zener effect. In the present case, the possibility of avalanche effect is small, since the enhanced field region is relatively small compared with the mean-free-pass (several nm) of an electron in Si (Fig. 4). On the other hand, the Zener effect can occur regardless of the size of the high electric field region.

The leakage current caused by the Zener effect[5] is estimated using the following equation:

$$I = BqnR^3P,$$

where B is a constant, q is the electronic charge, n is the number of precipitate particles, and P is the local Zener probability. The local Zener probability is given by the following equation[5]:

$$P = (qa\eta E/h)\exp(-\pi^2 m a E_g{}^2/h^2 q\eta E),$$

where a is the lattice constant, E is the external electric field, h is Plank's constant, m is the effective mass of an electron, and Eg is the energy band gap. Thus, leakage caused by the Zener effect is a function of the electric field. Calculated electric field dependence of the local Zener effect around two kinds of precipitates are shown in Fig. 5 (the broken lines) along with the experimental data. The calculated values show fairly good agreement with experimental results. Furthermore, the small temperature dependence of the degraded junction's large leakage current also can be explained by the small temperature dependence of the band gap (Eg) included in Zener probability.

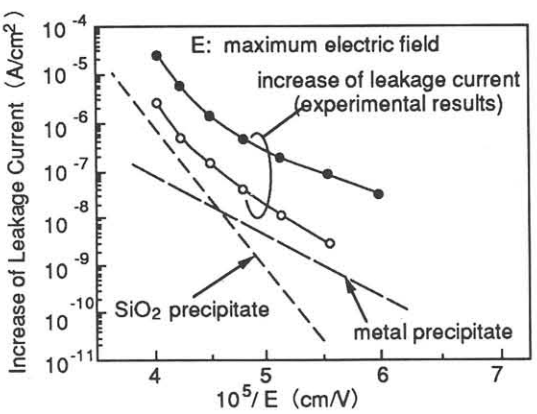

Fig. 5 Electric field dependence of leakage current caused by local Zener effect caused by precipitates.

Figure 6 shows the Zener probability as a function of precipitate depth. The probability reaches a maximum when the precipitate is the nearest the location of maximum electric field, and decreases drastically with increasing distance from the maximum field. Since precipitates are assumed to be introduced from the Si surface, the concentration of precipitate may be highest in the surface region. Therefore, junction degradation due to this local Zener effect probably can be suppressed if the maximum field point is kept away from the surface by controlling the depth profile of the electric field. Furthermore, the effect also can be suppressed by lowering the electric field using a linearly graded junction.

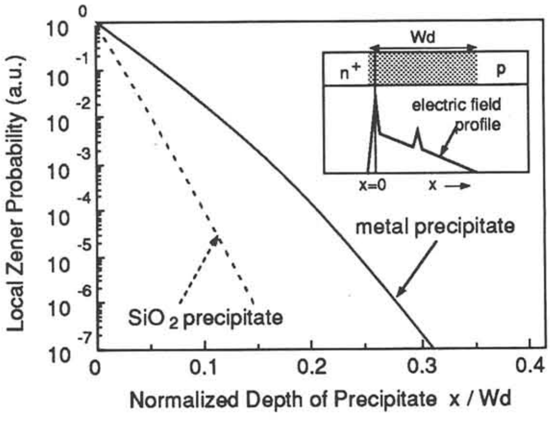

Fig. 6 Change of local Zener probability with depth of precipitate.

§ 4. Summary

Investigation into the origin of the extremely large leakage current of p-n junctions clarifies that the leakage is caused by the local Zener effect. Also, it is pointed out that the local Zener probability can be reduced by controlling the depth profile of the electric field.

References

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