# Hot Electron Emission from Silicon p-n Junctions Produced by Ion Implantation

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*Published in:*
Journal of Applied Physics

*Link to article, DOI:*
10.1063/1.1708025

*Publication date:*
1966

*Document Version*
Publisher's PDF, also known as Version of record

The following expression[7] for the dielectric constant can be obtained:

$$\epsilon' = \epsilon_\infty + \frac{4\pi n m \mu^2}{1+(m\mu/e)^2\omega^2}, \quad (2)$$

where $n$ is the number of ions or vacancy per unit volume, $m$ is the mass, $\mu$ is mobility, and other notation is standard. The expression for $\epsilon'$ is of the same form as the corresponding Debye equation. Jost[8] calculated the number of lattice defects under the assumption that the activation energy $E$ decreases by thermal expansion as the temperature rises. He obtained the following results:

$$n = \text{const} \times \exp\left(\frac{-\alpha V_0\, dE}{2k\ \ dV}\right) e^{-E/kT}, \quad (3)$$

where $V_0$ is the volume at 0°K and $\alpha$ is thermal expansion coefficient. This explains the experimental results, qualitatively, when substituted in Eq. (2).

The microwave conductivity $\sigma$ may be calculated from $\epsilon''$ by the relation

$$\sigma = \frac{\omega}{4\pi}\epsilon'' \cdot 1.1 \times 10^{-12} (\Omega^{-1}\text{-cm}^{-1}). \quad (4)$$

The activation energy of the vacancy $E$ in the intrinsic region was evaluated to be 1.98 eV, by plotting $\log\sigma$ vs $T^{-1}$ from the relation (4). Thus the obtained value agrees well, within the experimental error, with the 1.96 eV[9] obtained by the other method.

It would be expected that a density change should occur when an alkali halide crystal is $\gamma$-irradiated, because additional vacancies are generated. Lin[10] found that the linear expansion of the crystal is proportional to the average concentration of $F$ centers. In order to see the mentioned $F$ center effects, the crystal was irradiated with $^{60}$Co up to $1.4\times10^7$ R. Approximately, 6% of the increase in $\epsilon'$ was observed for the irradiated sample at room temperature, while the weakly irradiated sample does not show any observable change in $\epsilon'$.


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## Hot Electron Emission from Silicon $p$–$n$ Junctions Produced by Ion Implantation


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(Received 24 May 1966)

EMISSION of hot electrons from semiconductor $p$–$n$ junctions into vacuum was first observed from regions where the junctions intersected the surface.[1–6] This emission geometry limits the magnitude of the emitted current and makes a quantitive interpretation of the experimental results difficult. Results on electron emission from $p$–$n$ junctions parallel to the emitting surface were first reported by Moll, Meyer, and Bartelink.[7,8] They produced shallow $p$–$n$ junctions by diffusing phosphorus into $p$-type silicon. The emission current was measured as a function of the thickness of the neutral layer between the junction and the surface by a layer-removal technique. The energy distribution of the emitted electrons was determined by a retarding potential method.[7,8] It is, however, technologically difficult by traditional diffusion techniques to produce the desired shallow junctions which should be positioned preferably less than 1000 Å below the surface. It was therefore decided to investigate the use of ion-implantation techniques as an alternative method. Because the doping profile over the desired penetration distances can be controlled rather acurately by the energy of the impinging ions, one would expect ion implantation to be a convenient method for producing shallow junctions. We report in the present note on some preliminary results obtained by implantation of Cs and Na ions into $p$-type silicon.[9] Experimental results are given for the diode $I$–$V$ characteristics and the magnitude of the emission current as a function of the neutral layer thickness. Also the energy distribution of the emitted electrons has been determined.

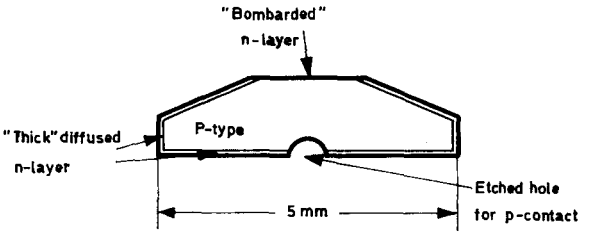


FIG. 1. Structure of silicon diode emitter.

The structure of the diode emitters is shown in Fig. 1. The base material is $p$-type silicon with a resistivity of about 0.1 Ω·cm. The "thick" $n$ layer of about 20 $\mu$ was obtained by usual phosphorus diffusion. This layer was lapped off at the top of the diode where the thin diode was subsequently to be produced. The purpose of the thick layer was to establish electrical contact to the thin layer.

The shallow $p$–$n$ junctions were produced by bombarding the exposed $p$-type region on top of the structure by Cs and Na ions. The energies of the ions ranged from 15 keV to 45 keV and the bombardment time was about 15 min with a current density of about 1 $\mu$A/cm$^2$. The diodes were held at a temperature of 500°C during the bombardment and the pressure in the chamber was about $10^{-5}$ Torr. More details of the experimental setup is given elsewhere.[10]

A typical $I$–$V$ characteristic is shown in Fig. 2. The neutral layer between the shallow $p$–$n$ junctions and the surface was thinned down by the boiling-water–HF-etching method,[7,8] where each cycle removes a layer thickness $l_c$ of about 33 Å. It is seen from Fig. 2 that the shallow junction breaks down before the thick junction.

The experimental results for the emission current $i_{em}$ as a function of the number $n_c$ of BW–HF cycles is shown in Fig. 3 for three different values of the total diode current $i_D$. The thickness

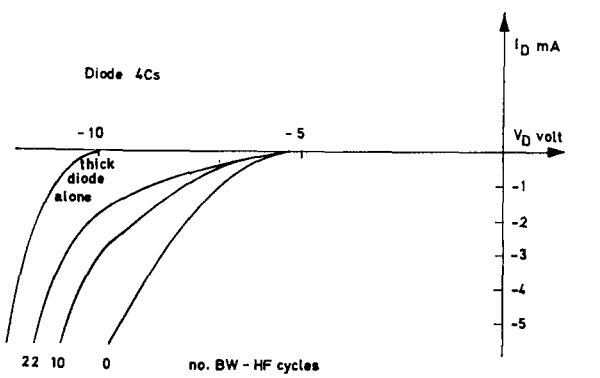


FIG. 2. Current–voltage characteristics of silicon diode emitter. The curve with the highest breakdown voltage was taken before the Cs bombardment.

$L_N$ of the neutral layer can be written

$$L_N = L_{NO} - n_c l_c, \tag{1}$$

where $L_{NO}$ is the original thickness which is of the order of 1000 Å for diode 4 Cs. The emission current $i_{em}$ is expected to vary with $L_N$ approximately as[8]

$$i_{em} = A \exp(-L_N/L_0), \tag{2}$$

where $A$ is a constant and $L_0$ is a characteristic length describing the interaction of the hot electrons with the phonons and bound valence electrons.[8] For low values of $n_c$, the variation of $i_{em}$ is seen to follow approximately the theoretical expression (2), but the values of $L_0$ obtained are appreciably higher than those found on the diffused junctions (50 Å).[8] Also the curves go through a maximum at values of $n_c$ between 5 to 20. These deviations are ascribed to the fact that a considerable transverse voltage drop is present across the shallow junctions produced by ion implantation so that the electrons are not emitted from an equipotential surface. This makes a quantitative analysis of the emission curves very complicated. It seems possible, however, to improve the surface conductivities of the shallow junctions by using a better vacuum.[11] Analogous results were found for junctions produced by Na ion bombardment. The surface conductivity in this case was somewhat higher than for the Cs diodes.

The results of a retarding potential measurement is shown in Fig. 4. The high-energy tail of the distribution function is approximately Maxwellian at low values of $n_c$ with a characteristic temperature $T_e$ such that $kT_e$ attains a value between 0.25 eV and 0.35 eV, which is lower than found for the diffused diodes ($kT_e \approx 0.5$ eV).[2]

The electron affinity $\varepsilon_{sf}$ was measured optically for the untreated and Cs-bombarded surfaces. No difference in electron affinity was detected within the experimental accuracy: $\varepsilon_{sf} = 3.9 \pm 0.1$ eV.

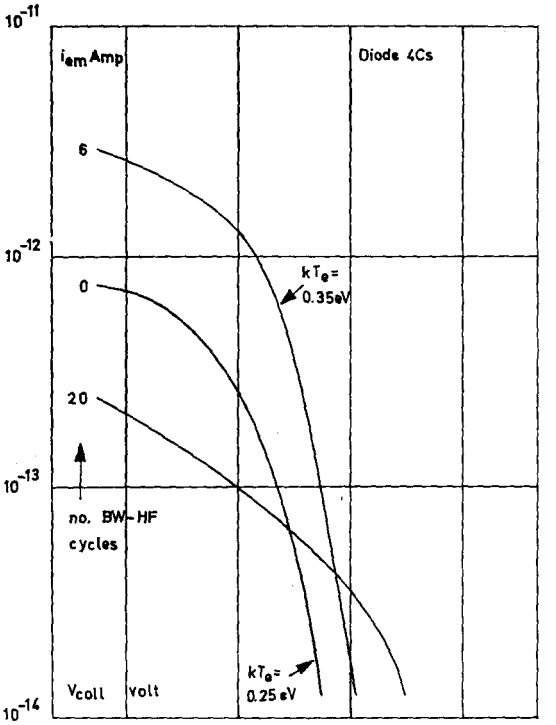


FIG. 4. Emission current $i_{em}$ as a function of the retarding collector potential $V_{coll}$ after different numbers of boiling-water–etching cycles.

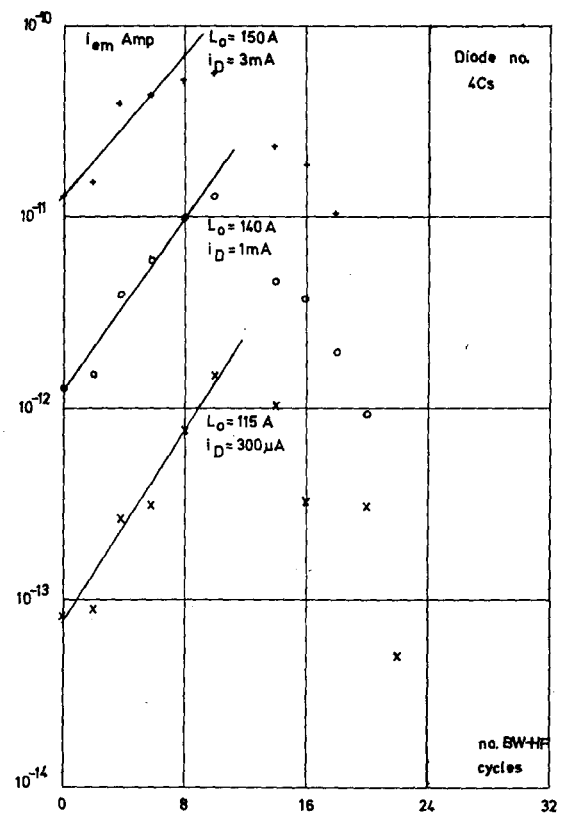


FIG. 3. Emission current $i_{em}$ as a function of the number of boiling-water–etching cycles with different values of the total diode current $i_D$. ×, ○, + are experimental points.

Thanks are due to Professor K. O. Nielsen and the accelerator group at Aarhus University for providing the ion beams, and to E. Hendricks and A. Noerballe for assistance with the experiments.

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## Autoradiographs in Pyrolytic Graphite

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(Received 25 April 1966)

SEVERAL studies of metal diffusion in pyrolytic graphite (PG) have recently been reported.[1–4] Although there are some differences in the interpretation of the data, the autoradiographic studies have all given similar results. The basic features are that (1) autoradiographs of tracer diffusion parallel to the deposition plane (taken with the film plane perpendicular to the deposition plane) are uniformly darkened, and (2) autoradiographs of tracer diffusion perpendicular to the deposition plane (taken with the film parallel to the deposition plane) show non-