

A REVIEW OF FRENKEL POOLE EMISSION

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The *p-n junction* for semiconductors has various mathematical models which try to explain the transport phenomena across the junctions for different semiconductor materials and at different temperatures. Here, we review Frenkel Poole Effect and concentrate in the domain of large Electric Fields where the additional increase in conductivity is independent of the Electric Field.

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I. INTRODUCTION

In the domain of very large electric fields E for both conductors and insulators, electrical conductivity exponentially tries to catch up till *breakdown* occurs. The limiting value of such an E is about 10^6V/cm and a few thousands of volts/cm for an insulator and conductor respectively. Experimentally, it had been noticed that in such fields, illumination of the semi-conductor surface lead to additional increases in conductivity, which could only be explained by their increase in number density, since their mobility wouldn't increase further. This led Frenkel to publish an article explaining the same in a note to *Phy. Rev. Letters*, 1938.

II. FRENKEL'S MATHEMATICAL MODEL

In the exorbitantly high electric field domain, the electrons can be considered to be acted upon by a field screened by the the positive ions. Of course the medium still contains some neutral polarizable atoms. Considering the screening due to polarization, the ionization potential reduces by a factor given by the permittivity of the medium, ϵ . [1]

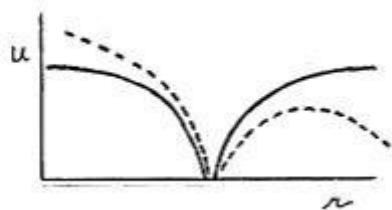


FIG. 1: Potential Energy as a function of distance from the positive ion. The dotted line is in the presence of the field while the bold one is in absence of external fields.[1]

In the figure above, we note that on increasing the external field E , following a mechanism similar to *Schottky Effect* inspired by Richardson's eponymous equation in 1901, decreases the energy. The height of the potential barrier in the field is thus lowered by:

$$\Delta U = eEr_0 + e^2/\epsilon r_0 \quad (1)$$

Here, r_0 is given by:

$$e^2 / \epsilon r_0^2 = eE$$

This thus gives us $r_0 = (e/\epsilon E)^{1/2}$. Replacing this back in the equation finally gives us:

$$\Delta U = 2eEr_0 = 2eE(e/\epsilon E)^{1/2} \quad (2)$$

Now, the number of free electrons due to thermal ionization is proportional to $e^{(-U_0+\Delta U)/2kT}$. However, the ionization potential energy had been reduced by a factor, . This thus gives us conductivity differing by:

$$\sigma = \sigma_0 e^{(e^3 E/\epsilon)^{1/2}/kT} \quad (3)$$

This as we see differs from the original Poole's Law, which was given by

$$\sigma = \sigma_0 e^{aE} \quad (4)$$

Now, the overall conductivity is thus given by:

$$\sigma = \sigma_0 e^{-U_0e/kT} e^{(e^3 E/\epsilon)^{1/2}/kT} \quad (5)$$

Making use of the modified form of Ohm's Law,

$$J = \sigma E \quad (6)$$

we obtain the standard form of *Frenkel-Poole Emission Formula* as follows:[3]

$$J \propto E \exp\left(\frac{-e(U_0 - \sqrt{eE/\pi\epsilon})}{k_B T}\right) \quad (7)$$

where:

1. J is the current density
2. E is the applied Electric Field
3. e is the electronic charge
4. U_0 is the voltage barrier in the absence of E that an electron must cross to move from one atom to another in the crystal
5. ϵ is the permittivity of the medium
6. k_B is the Boltzmann's constant
7. T is the absolute temperature

III. EXPERIMENTAL CONFIRMATION AND ANALYSIS

Frenkel's mathematical model was found to be in excellent agreement with P. Granofskaja and Joffe's experiments on pre-breakdown phenomena in electronic semi-conductors performed upto field strengths of about 50,000 volts/cm. [1]

What was unique about the above phenomena was that the effect of the applied field was *reduced* despite increasing temperature in the given semi-conductor. Electrons can move (slowly) through an insulator by the following method. The electrons are generally trapped in localized states (loosely speaking, they are "stuck" to a single atom, and not free to move around the crystal). Occasionally, random thermal fluctuations will give that electron enough energy to get out of its localized state, and move to the conduction band. Once there, the electron can move through the crystal, for a brief amount of time, before relaxing into another localized state (in other words, "sticking" to a different atom).[3]

The *Frenkel Poole effect* describes how, in a large electric field, the electron doesn't need as much thermal energy to get into the conduction band (because part of this energy comes from being pulled by the electric field), so it does not need as large a thermal fluctuation and will be able to move more frequently.

IV. APPLICATIONS AND SUMMARY

It remains the question about the transport mechanism which is responsible for transport in the case of over oxidized or under oxidized junctions. Several candidates have been checked. In a certain range of voltages and temperatures, Poole-Frenkel emission thermally stimulated emission of carriers from donor like trap sites seems to be the most probable.[2] Its voltage and temperature dependence is described by:

$$I \propto \sqrt{V} \exp(2a V/kT - eU_0/kT) \quad (8)$$

where

$$a = \left(\frac{e^3}{\pi \epsilon_0} \right)^{1/2}$$

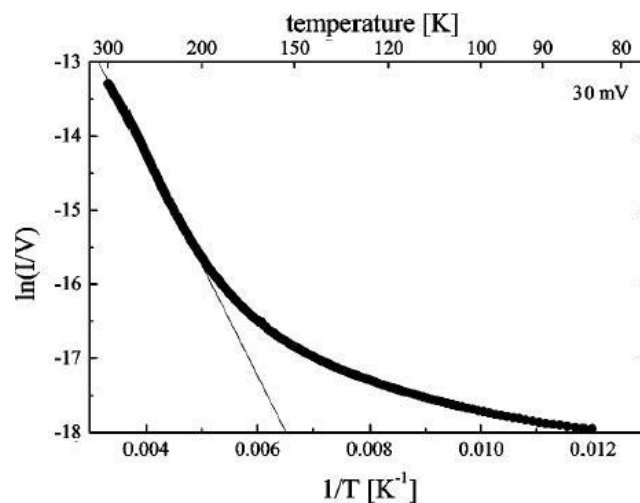


FIG. 2: A plot of $\ln(I/V)$ versus $1/T$ results in a straight line for the Poole-Frenkel effect, which is found here above 200 K, with an applied voltage of 30 mV.[2]

lines if *Poole-Frenkel conduction* is indeed the main conduction mechanism. These straight lines have been found for temperatures above 200 K at 30 mV bias voltage Fig. 2. According to the derivation by Frenkel, the dielectric constant enters the formula as the ability of the material surrounding a trap site to screen its positive charge.[2]

Frenkel states a radius of influence of the trap on the order of 30 *angstroms*. For our thin barriers, however, metallic material of the electrodes is met within this radius. This gives rise to a much more effective screening due to the high mobility of metal electrons, which in turn explains the much higher dielectric constant. Recently, these concepts have been used of in the fabrication of epitaxial layers on the semi-conductors especially benzotriazole and benzothiadiazole based organic devices.[4]

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