Static Current-Voltage Characteristics of Silicon n^+-i-n^+ Resistors at Liquid Helium Temperatures

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Abstract. The behaviour of the (I-V) characteristics is investigated in n^+-i-n^+ highly compensated Si resistors at temperatures 4.2-45K. The conduction mechanisms are discussed in detail here. The prebreakdown and breakdown regions of I-V characteristics were simulated by a one-dimensional model including the evidence of impurity high compensation and freeze out effects as well as the shallow-dopants impact ionisation by the injected hot carriers into the base. Negative resistance (S-type) phenomena are also observed on the characteristics for high injection current densities.

I. INTRODUCTION

The development of the cryogenic electronics during the last years, gave rise to the study of the behaviour of electrical transport parameters of semiconductor devices at low temperatures. Specially, integrated devices fabricated on high purity silicon, is of potential interest because of their advantages due to low leakage currents, reduced noise and parasitic capacity etc. [1-4].

The device operation at liquid helium temperatures (LHT) suffers from some anomalous phenomena associated mainly with the freeze out of the impurity atoms or with the shallow impact - ionisation by the injected hot carriers. Such phenomena as: hysterisis, kink effect, negative resistance, relaxation and transient behaviour, etc, observed on the current - voltage I-V characteristics are also more or less dependent on the applied electric field [2-7].

The low temperature current - voltage I-V behaviour of silicon based simple devices (diodes, resistors etc.) has been investigated previously by other authors [5-8]. Although a detailed theoretical analysis is a complex matter due to the above mentioned effects, the proposed analytical models are in good agreement with the experimental results [5].

In this work, the current - voltage characteristics of n^+-i-n^+ silicon devices are investigated in the temperature range 4.2-45 K. The devices were fabricated on high purity Si obtained by compensated shallow dopants (ratio k=1/2) with final donor concentration N_D - N_A = 2. 10^{12} cm^{-3}. The observed behaviour on our characteristics is different compared to that of resistors with similar structure [5], specially at very low temperatures. In order to simulate the I-V characteristics a one - dimensional simulator is proposed based on the Poisson and current continuity equations. Electrical transport parameters were also determined from the ohmic and current breakdown regions of the I-V characteristics.

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II. EXPERIMENTAL RESULTS

The silicon $n^+ - i - n^+$ devices were fabricated at the Institute of Microelectronics, NCSR "Demokritos" of Athens. A cross - sectional schematic is shown in figure 1.

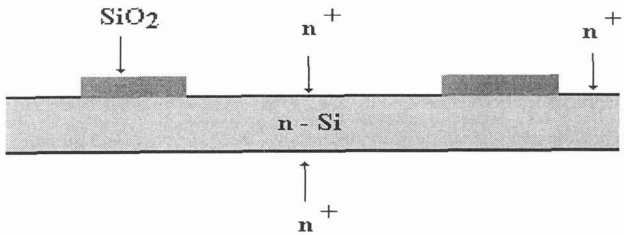

Figure. 1: Cross sectional schematic of a silicon $n^+ - i - n^+$ resistor.

The high-purity of the "i" region (base) of the device, is obtained by the compensation technique using silicon shallow dopants phosphorus and boron as donors and acceptors respectively. The high resistivity of the base was 5kΩ.cm and the final donor concentration $N_D - N_A$ was 2.10^{12} cm^{-3} with a compensation ratio k=1/2. The two n^+ regions were of about 10 μm thickness and doping concentration about 10^{20} cm^{-3}, created by phosphorus thermal diffusion. The part of the top surface, not covered by the n^+-region was passivated by a thermal SiO_2. The device thickness was 300μm , the total area 6x6 mm^2 and the injection area 5x5mm^2.

Variable temperature I-V measurements were performed in a liquid helium cryostat system. The continuous temperature control was obtained by using an OXFORD ITC4 Temperature Controller. For the constant current bias a programmable current source (KEITHLEY) was used.

The current - voltage characteristics of Si $n^+ - i - n^+$ devices were measured in the temperature range from 4.2K to 45K. The I-V experimental results for various temperatures are shown in figure 2 plotted on log-linear scale.

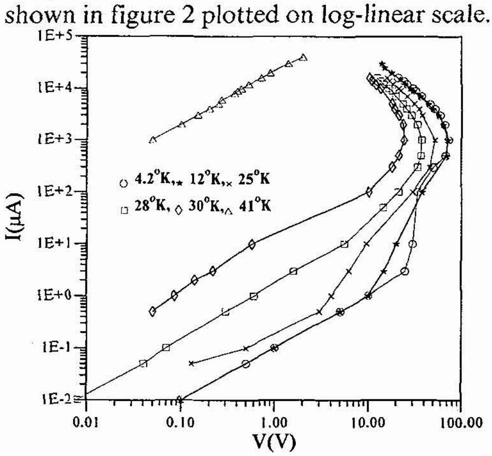

Figure. 2: I-V experimental results of Si $n^+ - i - n^+$ resistors for various temperatures.

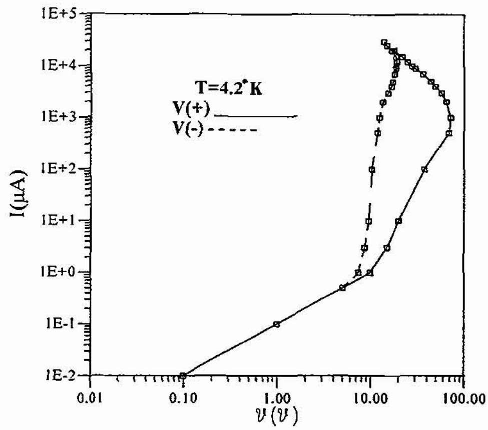

Figure 3:I-V characteristics subjected to forward and reverse bias voltage at 4·2K.

As it may be seen, at very low temperatures T< 30 K the resistors appear an ohmic prebreakdown behaviour up to a critical electric field slightly dependent on the temperature. At higher fields (E>200 V/cm) a current breakdown appears and for high - injection levels an S-type negative differential resistance (NDR) is observed on the characteristics. The shape of the breakdown and NDR regions is dependent on the sign of the applied voltage (forward or reverse) as we can see in figure 3. The above mentioned phenomena disappear at higher temperatures (T>30 K) where the characteristics present a clear ohmic behaviour.

3. THEORETICAL MODEL - DISCUSSION

3.1 Ohmic regime

As it is well known the current flow in a semiconductor subjected to an electric field E is described by the current equation:

$$J = \sigma . E \qquad (1)$$

Where the diffusion current is considered negligible compared to the drift current. The electrical conductivity due to a density of free electrons n_O, may be expressed by the formula:

$$\sigma = n_o \mu_n q \qquad (2)$$

Where μ_n is the ohmic mobility independent on the electric field E. For a compensated n-type material containing densities of donors and acceptors N_D and N_A respectively, the equilibrium density of the thermally activated free electrons is given by the relationship [9]:

$$n_o = \tfrac{N_c}{2}\left(\frac{1-k}{k}\right)\exp\left(-\frac{E_d}{k_B T}\right) \qquad (3)$$

where E_d is the activation energy of frozen-out donors, k is the compensation ratio and N_C the effective density of states: $N_C = 2 \times 10^{15} . T^{3/2}$. The above formula applied to silicon gives negligible carrier densities n_O for temperatures T<20 K.

The electrical conductivity values versus temperature were determined from the linear region at the I-V characteristics. Plotting the results of σ versus 1/T in log-linear scale (figure 4), we can observe the discussed two regions.

For temperatures between 20K and 41K the dominant conduction mechanism is the thermal activation of electrons of frozen out donors, into the conduction band. In the temperature range 4.2 - 20 K a different conduction mechanism is dominant. This is due to "hopping" of bound electrons from uncompensated donor atoms to neighbouring compensated ones without the need of excitation into the conduction band. This mechanism called, impurity conduction [10,11] depends critically on the majority impurity densities and on the degree of compensation. A general relationship simulating the electrical conductivity results in all the investigated temperature range, can be written as follows:

$$\sigma = \alpha \cdot T^{\frac{3}{2}} \cdot \exp\left(-\tfrac{E_d}{k_B T}\right) + \beta \cdot \exp\left(-\tfrac{E_1}{k_B T}\right) + \gamma \qquad (4)$$

The parameters α,β,γ are mainly dependent on the temperature and the mobility of carriers. The activation energy of donors E_d, determined from the results of figure 4, is found 0.048eV and is in good agreement to the expected value for the Phosphorus in Si. The impurity conduction activation energy E_1 is found 0.011 eV. This value is in consequence to the theoretically calculated for highly compensated semiconductors [11].

We can conclude that the above conduction behaviour is not of typical space-charge limited type (quadratic I-V law) observed by other authors [5] on uncompensated n^+-n-n^+ Si resistors in LHT range. We support that this difference is due to the high compensation level of our samples resulting in impurity conduction.

3.2 Impact ionisation regime

As we can see (fig. 2), beyond a critical electric field the electric current increases more rapidly than in the linear regime. The conduction mechanism dominating here is the impact ionisation of the frozen-out shallow donors by the injected hot electrons from n^+ regions of the device. Due to the very large values of the carrier mobility at very low temperatures [12], the necessary critical field for impact avalanche effect is relatively low (100-300 V/cm) for the Si, dependent also on the compensation and impurity concentrations level. The observed critical fields are also slightly dependent on the temperature and in agreement to the reported ones concerning compensated Si at LHT [13,14].

The ionisation degree of impurities as a function of the electric field is determined by the dynamic equilibrium state between the ionisation rate by impact and the recombination rate of free carriers by ionised impurities. The rate of the ionised donors (space-charge density) is given by the continuity equation:

$$e\,\frac{dN^+_D}{dt} = eA(E)N_D{}^o\,.\,n - eB(E)N_D{}^+\,.\,n \qquad (5)$$

Where $N_D^+ = N_D - N_D^o$. For the steady state case we conclude that:

$$N_D^+ = N_D\,\frac{A(E)}{A(E)+B(E)} \qquad (6)$$

and $N_d{}^o$ is the neutral donor density. A(E) and B(E) are the field dependent rates for impact ionisation and thermal capture respectively [5].

For the simulation we consider a one-dimensional device. Since we are interested in the intermediate temperature region as well, in writing down the Poisson's equation, thermal excitation of carriers is not neglected. Additionally, impact has also been included in the analysis as a means to explain the breakdown effect. Thus the Poisson's equation reads:

$$\frac{dE}{dx} = \frac{e}{\varepsilon_s}\left[n(x) - n_o + \frac{k-1}{k}\,.\,N_D\,\frac{n(x)-n_o}{(k-1)n(x)+n_o}\right] - \frac{e}{\varepsilon_s}N_D\,\frac{A(E)}{A(E)+B(E)} \qquad (7)$$

Where ε_s is the dielectric constant of Si and n(x) the carrier concentration measured from the cathode. The first term amounts for the thermal excitation in a compensated semiconductor. The second term describes the impact ionisation. In the limit $n_o \rightarrow o$ and n_o impact, Poisson's equation reduces to:

$$\frac{dE}{dx} = \frac{e}{\varepsilon_s}n(x) + \frac{e}{\varepsilon_s}\frac{N_D}{k_B} \qquad (8)$$

a case that may be easily studied by the regional approximation method proposed by Lambert [15] and which predicts a breakdown effect. The set of equations (1), (2) and (7) was integrated numerically and a sample result is shown in figure 5. The field dependence of the electron mobility has also been taken into account.

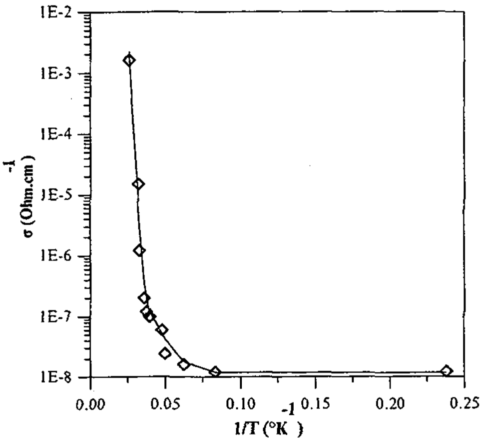

Figure 4: Electrical conductivity results versus 1/T in log-linear scale.

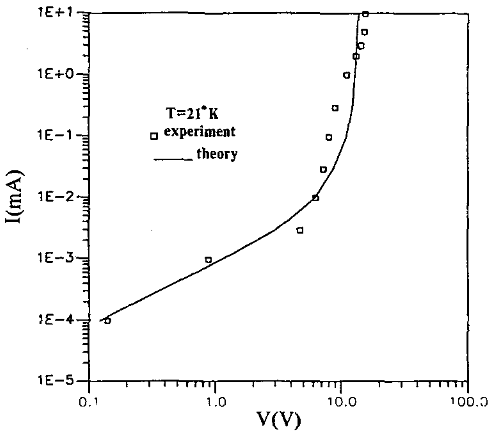

Figure 5 : Comparison between experimental curve and analytical evaluation at 21⁰ K.

The application of a reverse bias results in a different breakdown region of the I-V characteristics compared to the forward bias case (Figure 5). In the reverse bias case electron accumulation takes place in the n^+ top region and a depletion state is formed near the back contact region. This change in the distribution of the base space charge decreases the device resistivity resulting in a reduction of the required critical electric field for the impact avalanche.

The NDR effect of the breakdown region observed for high current injection levels is also associated to the impact avalanche multiplication of the tree carriers into the base. Above a critical current value the increase of the device conductance reduces the electric field into the base and the current increases again. This effect is accompanied by a voltage drop across the device and an S-type NDR appears [16].

The effects discussed above related obviously to the freeze-out of the dopants, disappear at temperatures T>41K where the dopants have been fully ionized thermally (Ohmic law). A further quantitative analysis will be reported in the future.

4. CONCLUSIONS

An investigation of the I-V characteristics of n^+ -i- n^+ devices at LHT has been presented. From the experimental data and simulation it is shown that the impurity conduction mechanism dominates at T<20K due to the high compensation level. The impact avalanche ionisation phenomena appear at low critical electric fields. An S-type NDR effect is shown above a critical high injection level in the breakdown region at the LHT.

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