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Z-element's Mechanism and I-V Characteristic Simulation

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Abstract On the basis of confirmation of the basic p^+-ν-n^- diode structure of Z-element, we start with analyzing the charge transportation theory. According to the action of background and injected carrier in the different operating regions and by solving the basic device equation set by numerical simulation, a conclusion can be drawn that *I-V* characteristic curve of Z-element shows itself the S-shaped negative resistance and approaches the existing experimental results. And the device performance is rather sensitive to the related technological parameters and material parameters. The achievement in the area of studying Z-element indicates that Z-element is expected to have wide prospects for application in the sensor's fields, such as the temperature-sensitive, light-sensitive and magnet-sensitive sensors.

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1 Introduction

Z Sensitive element can be used to not only detect the temperature, intensity of magnetic field, ultraviolet ray intensity directly, but also measure the related physical parameters indirectly according to the variations of magnetic field. Especially, the output of digital pulse signal with large amplitude of Z-element, without using the amplifier or A/D converter, and its connection with the digital instrument directly can both simplify the applied circuit greatly. Since it was made known to the world in 1990, its potential superiority has attracted the electronics experts all over the world to pay their attentions to it[1~9]. We can say that the electronic products composed of Z-element, such as various digital sensors and industrial transducers etc., are expected to have wide use in applied electronic technology.

However, few detailed reports on the subject of Z-element can be found in the literature. Even its working mechanism remains to be solved. Why a Z-element, merely a special p-n junction has such unusual functions? In this paper, we will simulate its *I-V* characteris-

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tic curve and try to find the relation between the key parameters of Z-element and its device characteristics. We hope it could make sense for the future research and development in this field.

2 Structure and mechanism

2.1 Structure of Z-element

The substrate used to fabricate Z-element is n-type bi-polished silicon of 500μm's thick with high-resistivity. A p^+-n junction was formed after diffusing Al into Si substrate. At the temperature of 900±0.5℃, gold, copper, or platinum was penetratingly diffused into the wafer. Then the wafer was thinned to 300μm's thick. An ohmic contact was done after Ni was evaporated on both front and rear surfaces of the wafer. Then dicing into the appropriate size, ranging from typical 2×2mm to maximum 2×15mm, and packing, a Z-element was finally completed.

When the donor concentration of n-type silicon is 10^{15}～10^{13}cm^{-3} or so, with the concentration of gold being 1.1×10^{14}cm^{-3}, owing to the action of compensation, the Fermi level E_F of silicon is 0.53eV below the bottom of conduction band, while the acceptor level of gold is 0.54eV, so the almost half in acceptor levels is empty. Providing the concentration of gold is 6.7×10^{13}cm^{-3}, nearly the whole acceptor levels can be filled up. So, a conclusion is drawn that negative resistance can be produced only in high-compensation silicon-material.

When gold diffused into n-typed silicon, a compensated high-resistivity semiconductor is formed. Only a Ni layer is impossible to form an excellent ohmic contact with Si substrate. An n^+-region is necessary for an injection of carrier not being limited by the electrode. Therefore, Z-element is a p^+-ν-n^+ diode with gold-doping for compensation (shown in Fig. 1). The length of ν-region is about 200～500μm, which is far longer than the diffusion lengths of electron or hole in silicon, so it is a long p^+-ν-n^+ diode.

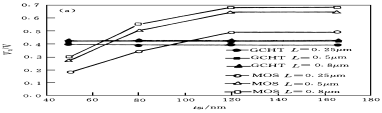


Figure 1 Structure of Z-element

2.2 Process of charge transportation

The forward characteristic *I*-*V* curve indicates that Z-element is S-shaped negative resistance device (see Fig. 2). Concerning the ν-region, low concentration of doping makes it to be of high resistivity, while with the compensation of high-concentration of Au doping, the resistivity would enhance further, at the same time introducing a large number of deep-level traps or combination centres which can cut the lifetime τ_0 of free carrier. When τ_0 is shorter than the dielectric relaxation time, the relaxation state would come into being at a certain period during the operating time of the device. On a high level of injection,

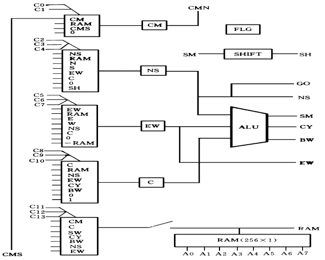


Figure 2 *I*-*V* characteristic of Z-element

space charge conduction appears, forming the space charge limited (SCL) current Long ν-region ensures the combination centre to give full play during the whole journey of charge transportation Moreover, this is a double-injection device, i e , when increasing the forward bias, the electrons will be injected from the cathode, while holes from anode Therefore, we have to consider not only the influence of space charge and carrier capture on conductance, but also the restriction to the current of the space charge with double-polarities and the recombination action caused by double-injection The mechanism is rather complicated, so is the analysis and simulation of the device

However, the physical mechanism of Z-element obeys the essential principles and regulations of charge transportation in semiconductor, such as principle of continuity of electric current, Poisson equation (neglect of localized state charge distribution) and charge conjugation conservation etc[10]. Generally speaking, the electricity current passing through the Z-element is consisted of background carrier current and space charge limited current, which do different contribution at different bias range So, we adopt the simulative method to solve the three sets of essential equation From the results, we can see the characteristics of terminal current and voltage, which is tallied with the real situation

1) Ohmic current region

If the positive bias is low, most of the holes injected from p^+ area are captured by Au deep levels so that the current through the Z-element is mainly thermal excited electron current (background current). The relation between I and V is linear as follows

$$J_1 = qn_0\mu_nE = qn_0\mu_nV/d, \tag{1}$$

Here n_0 is the concentration of thermal-excited free electrons, μ_n is the electron mobility, V is positive voltage and d is the length of ν-region

2) Space charge limited current region

With the increasing of positive bias, the concentration of electrons or holes injected becomes far higher than that of the thermal-excited free carriers As the electrons or holes becoming the main contributor of current, space charge limited current is formed At the beginning, since most of the holes injected are still captured by Au deep levels and only a few holes are engaged in conducting current, accompanying the recombination of electrons or holes injected and the emission of holes having been captured by Au traps, the current, which is mainly electron current, drifted off the linear relation in ohmic region and presented a square-law relation between the current and bias as following

$$J_2 = q\mu_n\mu_p\tau n_0V^2/d^3, \quad \tau = (1 + C_n/C_p)/(C_nN_T). \tag{12}$$

Here τ is lifetime of carrier, C_n and C_p are the capturing rate of electrons and holes respectively, N_T is the density of traps or centres, all of above have direct relationship with the concentration and distribution of Au

With the positive bias going on increasing, to some critical voltage, at which the transit-time of carriers across ν region approaches its lifetime, nagative resistance emerges because of the capture and migration of carriers Easy as it seems for Ni-electrode to form an ohmic contact with n^+-layer, the perfect ohmic contact does not exist at all, because the difference between parts of crystalline plane, which is uneven and incomplete in microcosm, leads to the uneven between electrode and crystalline plane. In fact, when the intensity of electric field is strong enough, the injection of carrier from electrode to the material is like the filament injection. At the same time, current filaments begin to act the conductive mechanism, and become more remarkable alongside the electrical field growing stronger. Till the lifetime of electrons equals to that of holes, the electronic current transfers into space charge limited current with two kinds of carriers

$$J_3 = 9/8\epsilon(\mu_n + \mu_p)V^2/d^3, \tag{3}$$

Here ϵ is the dielectric constant of silicon.

With further increasing of positive bias, the electrons and holes injected reaching a higher level, at which the rate of injection is higher than recombination rate, and the current is similar to the double-injection of insulator, including two kinds of space charge limited carriers. The relation between current and voltage is cubicity

$$J_4 = (125/18)\epsilon\mu_n\mu_p\tau V^3/d^5. \tag{4}$$

According to the above-mentioned *I*-*V* characteristic expressions (1) to (4), we can do its *I*-*V* characteristic simulation analysis.

3 Simulation analysis and proving of Z-element's I-V characteristics

In order to simplify the calculation and analysis during our following simulation, we firstly do normalized treatment on current and voltage:

$$V_0 = d^2 c_n N_T/\mu_n, \tag{5}$$

$$J_0 = [\epsilon d(C_n N_T)^2]/\mu_n. \tag{6}$$

And the value of each parameter is as followed:

$q = 1.6\times10^{-19}$C; $\epsilon = 11.9\times8.854\times10^{-14}$F/cm; $d = 10^{-2}$cm;

$\mu_n = 750$cm^2/(V·s); $\mu_p = 350$cm^2/(V·s); $N_T = N_{Au} = 10^{16}$cm^{-3}.

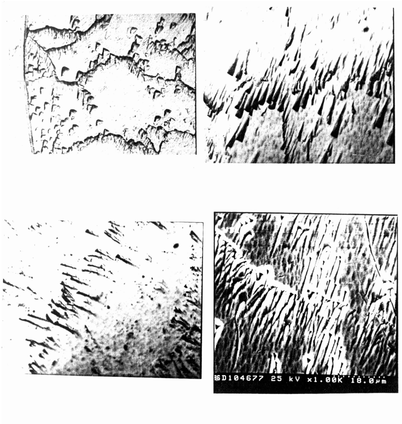
From (1) to (4), we can get an *I*-*V* characteristic (shown in Fig. 3) of Z-element after simulation. The figure proves that S-shaped negative resistance can be obtained by way of segmented simulation. And the shape of the *I*-*V* curve will change a lot if choosing differnt parameters.

Figure 3(a) and 3(b) are respectively *I*-*V* curves with different values of C_p/C_n. The bigger the C_p/C_n is, the broader the negative resistance region is (with the increasing of threshold voltage V_{th} at the same time); whereas, the more narrow the region of negative resistance. This is because the threshold voltages V_{th} of negative resistance region and break voltage V_M have the following relation:

$$V_{th} = (C_p/C_n)V_M$$

So the range of negative resistance region is:

$$\Delta V = V_{th} - V_M = (C_p/C_n - 1)V_M, \tag{8}$$



(a) ×1000 (b) ×1000

(c) ×1000 (d) ×1000

Figure 3 Simulated I-V Characteristic of Z-Element

When $C_p = C_n$, the negative resistance region disappears Since C_p, C_n are concerning with not only the concentration of impurity with deep levels and the position of the levels, but also with the perfectness of material (including the number of defects and dislocations) closely. It is necessary to control them strictly during the production process

It is also found that according to the theoretical analysis, at the point of break voltage, the value J_3 is far smaller than value J_4, i.e., the relation between current and voltage after negative-resistance region jumps to cubicity instead of square law. No J_3's value is shown in the Figure 3, as might have something to do with the choosing of material parameters

Changing some key parameters, the characteristics of device varies obviously (see Table 1), which proves that Z-element is a kind of processing sensitive device Therefore, if adjusting the electric and geometric parameters by way of processing control, we can obtain all kinds of sensors meeting the different requirements on characteristics

Figure 4 gives the experimental results, in which (a), (b) are respectively the I-V curve corresponding with the common coordinate and logarithmic coordinates

Figure 4 Experimental I-V curve of Z-element

Conclusion is reached after comparing Figure 2, 3 and 4 that the simulative I-V curve for Z-element's coincides qualitatively with the experimental results published by Zotov as well as approaches the testing results of sample provided by Harbin Novic Company. Obviously, the simulation results by theoretical analysis can reflect the physical essence of Z-element very well.

Table 1 Influence of different key parameter on characteristics of Z-elements

Parameters \ Charachteristics		V_{th}/V	V_M/V	$J_0/(A\cdot cm^{-2})$	V_0/V	$\Delta V/V$
$d/\mu m$	100	25	10	0.067	8	15
	200	100	40	0.135	32	60
	300	225	90	0.202	72	135
N_T/cm^{-3}	10^{16}	25	10	0.067	8	15
	5×10^{15}	12.5	5	0.017	4	7.5
	2×10^{15}	5	2	0.003	1.6	3
$C_n = 8\times10^{-9} cm^3/s$ $C_p = 2\times10^{-8} cm^3/s$		25	10	0.067	8	15
$C_n = 3\times10^{-8} cm^3/s$ $C_p = 3\times10^{-7} cm^3/s$		375	37.5	0.948	30	337.5

According to the test on the temperature-sensitive, light-sensitive and magnetic-sensitive performances of Z-element, after analyzing the operating mechanism, the prospect of a vast range of applications of Z-element can be seen in various fields, such as in data acquisition and monition of temperature, light or magnetic field and their digital processing etc.

4 Conclusion

1) Z-element is a special diode with long p^+-ν-n^- structure, being as S-shaped of negative resistance device.

2) The impurity in Z-element such as Au etc. with deep level, plays a principal role in forming the negative resistance.

3) The high sensitivity of Z-element to the related parameters of material and key processing determines the wide and potential application.

4) The I-V characteristic curve we obtained approaches the existing results of experiment.

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