Evaluation of the specific interfacial contact resistance for Al /p-Si contact

H. Amer[a], H. Tork[a], A.K. Aboul Seoud[b], and M. Rizk[b]

[a] *Institute of Graduate Studies and Research , Alexandria University, Alexandria, Egypt*

[b] *Electrical Eng., Dept., Faculty of Eng., Alexandria University, Alexandria, Egypt*

The specific interfacial resistance refers to the metal-semiconductor interface. It is a very useful term for ohmic contacts because it is independent of the contact area. In this work, the effect of the different sintering temperatures and sintering times for the Al /p-Si, specific contact resistance have been accurately determined. The data was carried out by a computer program using an interfacing system technique between a specially designed oven furnace and the computer. The specific contact resistance has been determined using the three point probe method. The specific contact resistance decreases from $0.8 \cdot 10^{-6}$ ohm -cm^2 to $0.01 \cdot 10^{-6}$ ohm -cm^2 for an increase in the sintering temperature from 573 K to 823 K. The sintering time has no effect on the specific contact resistance. It is hoped that this study can be used in the future as a guideline in developing ohmic contacts for various semiconductor devices.

إن المقاومة النوعية هي مقاومة الطبقة المتداخلة بين شبه الموصل والمعدن. إنها عنصر هام جداً لحساب مقاومة الوصلة، و حيث أنها لا تعتمد على مساحة الوصلة فإنها عامل ملائم عند مقارنة الوصلات ذات المساحات المختلفة. في هذا البحث تم تحديد بكفاءة تأثير المعالجة الحرارية عند درجات الحرارة المختلفة وزمن هذه المعالجة على المقاومة النوعية. تم الحصول على هذه النتائج عن طريق برنامج على الحاسب الآلي متصل بفرن صمم خصيصاً لهذا الغرض – تم حساب المقاومة النوعية عن طريق حساب الثلاث وصلات. وقد وجد أن المقاومة النوعية تقل من ٠,٧×١٠^-٦ أوم.سم^٢ إلى ٠,٠١×١٠^-٦ أوم.سم^٢ عندما رفعنا درجة المعالجة الحرارية من ٥٧٣ كلفن إلى ٨٢٣ كلفن، كما وجد أن زمن المعالجة الحرارية ليس له تأثير على المقاومة النوعية للوصلة. نأمل أن تكون هذه الدراسة نواة عند دراسة وصلات لنبائض شبه موصلة.

Keywords: Ohmic contact, Characterization, Conduction mechanism

1. Introduction

Metallization contact systems are a fundamental component to all semiconductor devices and integrated circuits. They provide the correct electrical link between the active region of the semiconductor and the external circuit. In the case of an integrated circuit, they interconnect with great precision the circuit elements to provide the desired conducting paths. The primary concern in the choice of a metallization contact is to ensure that the metal has the desired electrical properties.

Two distinct contacts can be realized at the metal-semiconductor contact. These are the ohmic (resistive) and the Schottky (rectifying) contacts.

Previous work on Al/p-Si contact used to sinter the contacts before the measurements were taken. In the present work, the measurements of the current and voltage were taken during the heat-treatment, and so the effect of the sintering temperatures and sintering times are studied more precisely in order to obtain a low resistance ohmic contact. Inspite of the fact that the effects of heat treatment has to be considered at the normal operating temperature (room temperature),the measurements in this paper have been taken at the annealing temperature; This may be used to investigate the evolution of the specific contact resistance during heat treatment only.

2. Theoretical approach

The only independent parameter that describes the resistance of the interface at the contact is called the specific contact resistivety. It's unit is ohm-cm^2 i.e. it is the resistance of a unit area of the thin interfacial layer between the bulk metal and the semiconductor

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substrate. A theoretical definition for the specific contact resistance is

$$\rho_c = dV/dJ \Big|_{J=0}, \quad (1)$$

where J is the current density and V is the voltage drop across the interface.

The implicit assumption underlying eq. (1) is that J is uniform across the contact interface. Eq. (1) is applied to contacts that over specified range of currents are ohmic.

2.1. Effect of heat treatment

Most contacts used in semiconductor devices are subjected to heat treatment. This may be deliberately to promote adhesion of the metal to the semiconductor or they are unavoidable because a high temperature is needed for other processing stages to occur after the metal is deposited.

2.2. The Al-Si system

During sintering, Si from the single crystal substrate diffuses into the Al through the grain boundaries,this is called solubility, concomitantly, Al diffuses to the substrate surface, this is called penetration. The extent of the penetration is greater for higher temperatures because diffusion rates are higher and there is a higher solubility of Si in Al.

Since the solubility of Si in Al decreases with decreasing temperature, Al becomes supersaturated with Si during cooling from the sintering temperature. The supersaturation is highest in the region adjacent to the contact from which Si was originally depleted. During cooling the Si precipitates from the solution in the Al forming particles at the Al boundaries, and at the same time forming an epitaxial layer on the Si in the contact region.So the effective density of the dopant in the semiconductor; is increased, the barrier gets thinner (the depletion width gets smaller) and thermionic or even field emission occurs.A p^+-p system is formed.

The calculation of ρ_c has been derived from different approaches [1-5]. Unfortunately, the published curves do not emphasize the practical regimes used for Si contacts and more detailed curves are needed.

Furthermore, those results did not consider in details the relevant tunneling effective masses, and the respective effective dielectric constant that results in n and p-type materials under the effect of temperature . In this study the calculation of the effective masses of carriers and relative dielectric constants have been taken into consideration.

2.3. The current transport

The value of ρ_c is determined for Field Emission (FE), Thermionic Emission (TE) and Thermionic Field Emission (TFE) transports. The most widely accepted model for FE and TFE is given by Padovani and Straton [6-7] and is used in this work. Yu [4] has utilized his theory to calculate ρ_c, he used a useful term E_{00} (a parameter which plays an important role in tunneling theory. It has the dimensions of energy divided by charge) and is defined as

$$E_{00}=(q\hbar/2)\sqrt{N/m^*_{tun}\,\varepsilon_s}\,, \quad (2)$$

where m^*_{tun} is the tunneling effective mass of electrons or holes in the semiconductor, N is the doping concentration , ε_s is the permitivity of the semiconductor, q is the electronic charge and $\hbar$ is the modified Plank's constant. For any particular ellipsoid of constant energy surface in K space, the m^*_{tun} is given by[8]

$$m^*_{tun} = \left(\frac{l^2}{m_x}+\frac{m^2}{m_y}+\frac{n^2}{m_z}\right)^{-1}, \quad (3)$$

where l, m and n are the direction cosines of the ellipsoid relative to the principle axes, and m_x, m_y, and m_z are the tensor masses . The dominant current conduction mechanism and thus ρ_c can be divided into three regions.

In the low doping region $kT/E_{00}>>1$, TE dominates and

$$\rho_c=(k/qA^{**}T)\exp(\phi_b/kT). \quad (4)$$

Where A^{**} is the modified Richardson constant [9] and ϕ_b is the barrier height.

In the medium doping region $kT / E_{00} \approx 1$, FE

dominates and,

$$\rho_c = \frac{k\sqrt{E_{00}}}{qA^{**}T\sqrt{\pi(\phi_b+u_f)}}\cosh\left(\frac{E_{00}}{kT}\right)$$
$$\coth\left(\frac{E_{00}}{kT}\right)\cdot\exp\left(\frac{\phi_b+u_f}{E_0}-\frac{u_f}{kT}\right), \qquad (5)$$

where u_f is the Fermi level with respect to the band edge (positive when generate), T is the absolute temperature, k is the Boltzmann constant and A^* is the effective Richardson constant and is equal to

$$A^* = M\,4\,\pi\,m^*\,q\,k^2\,/\,h^3, \qquad (6)$$

and

$$E_0 = E_{00}\coth(E_{00}\,/\,kT). \qquad (7)$$

E_0 is a measure of the tunneling probability in TFE and TE, M is the number of equivalent ellipsoids corresponding to the minimum tunneling effective mass and m^* is the effective mass of electrons and holes and is different from m^*_{tun} and is given by[10]

$$m^* = (l^2 m_y m_z + m^2 m_x m_z + n^2 m_x m_y)^{1/2}.$$

Eq. (4) is valid if;

$$\frac{\cosh^2\left(\frac{E_{00}}{kT}\right)}{\sinh^3\left(\frac{E_{00}}{kT}\right)} < \frac{2(\phi_b+u_f)}{3E_{00}}, \qquad (8)$$

for higher doping, $kT\,/\,E_{00} << 1$, TFE dominates and

$$\rho_c = \left(\frac{A^*qT\,\pi}{k\sin(\pi ckT)}\exp\left(\frac{-\phi_b}{E_{00}}\right) - \frac{A^*q}{ck^2}\exp\left(\frac{-\phi_b}{E_{00}}-c\,u_f\right)\right)^{-1}, \qquad (9)$$

where ;

$$c = \frac{1}{2E_{00}}\ln\left(\frac{4\phi_b}{u_f}\right). \qquad (10)$$

3. Experimental procedure

The p-type Si[100] crystals used in these experiments are doped with boron of doping concentration $N_A = 10^{24}\ m^{-3}$. Prior to metal deposition the samples were degreased by immersing them successively in propanol and HF 40%, they are then dried by using a filter paper. A thick layer of Al was evaporated on the polished surface of the sample in the vacuum chamber Edward E 306A. Circular dots of .5 mm in diameter were obtained by using a special mask .The measured specific contact resistance at room temperature was $5{\cdot}10^{-6}$ ohm-cm^2

4. Results and discussion

The I-V characteristics of the metal semiconductor junction are drawn using the Grapher program at six different temperatures 573K, 623K, 673K, 723K, 773K and 823K. Figs. 1 to 6 show these I-V characteristics at the different sintering times. The readings of the currents and voltages were obtained using the three point probe method [11]. The specific contact resistance ρ_c are obtained from the slope of the best fitting lines to the I-V characteristics.

Fig.7 shows the effect of the sintering temperatures on ρ_c ,the decrease in ρ_c with the increase of the temperature is due to the increase of the doping concentration just under the metal contact. Fig. 8 shows the relation between ρ_c and the sintering time, the increase of the sintering time has no effect on the specific contact resistance ρ_c because the contact has reached its thermal stability.

The evaluation of N_A was obtained from the solid solubility of Al in Si [12]. The values of N_A at the different temperatures are reported in table 1.

The theoretical dependence of the specific contact resistance ρ_c on the doping concentration was published by Piotrowska [13].

Table 1
Values of N_A at different temperatures

T (K)	300	573	623	673	723	773	823
N_A/m^3	10^{24}	$5x10^{25}$	$9x10^{25}$	10^{26}	$1.5x10^{26}$	$2x10^{26}$	$2.5x10^{26}$

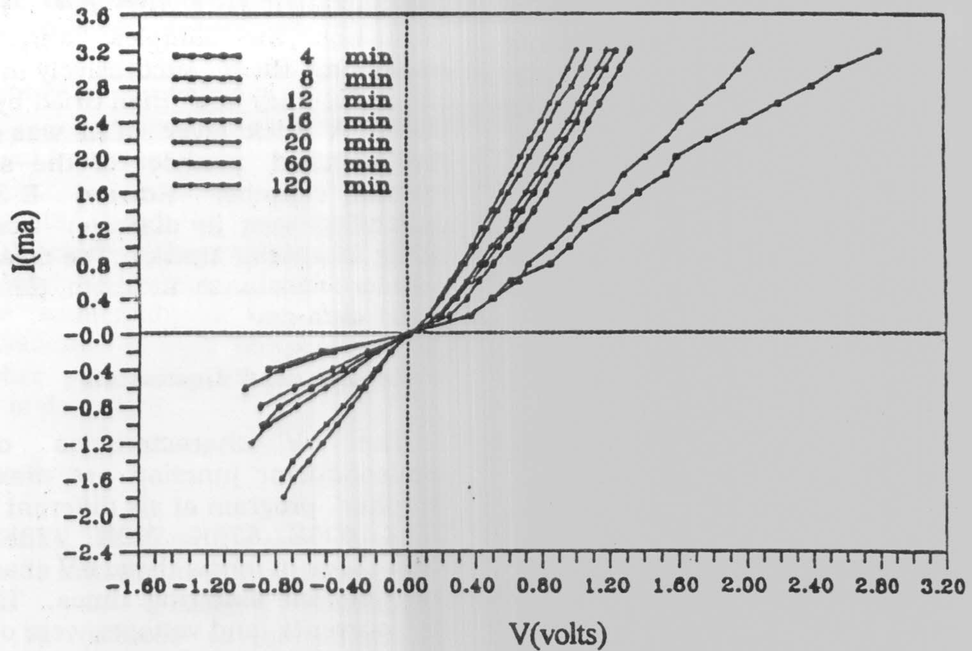

Fig. 1. The I-V characteristics at 537K and different sintering times.

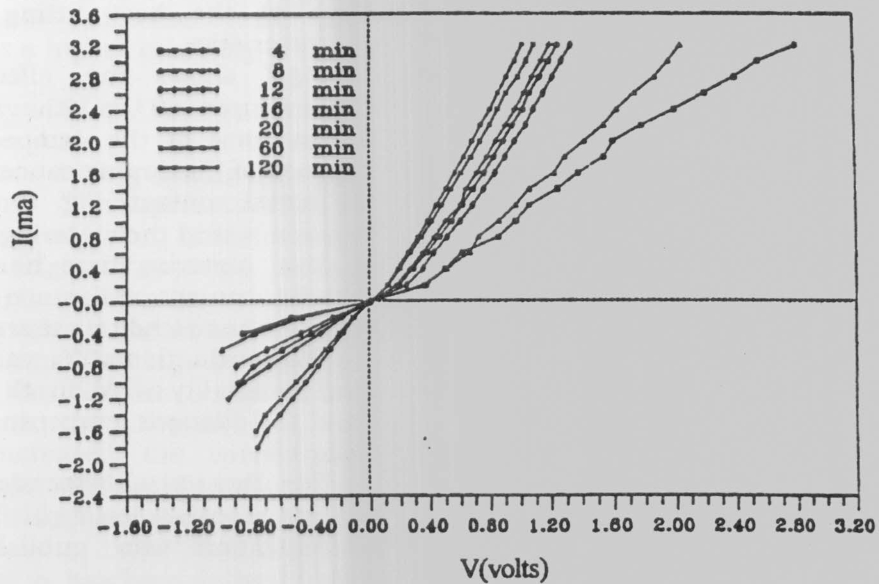

Fig. 2. The I-V characteristics at 623K and different sintering times.

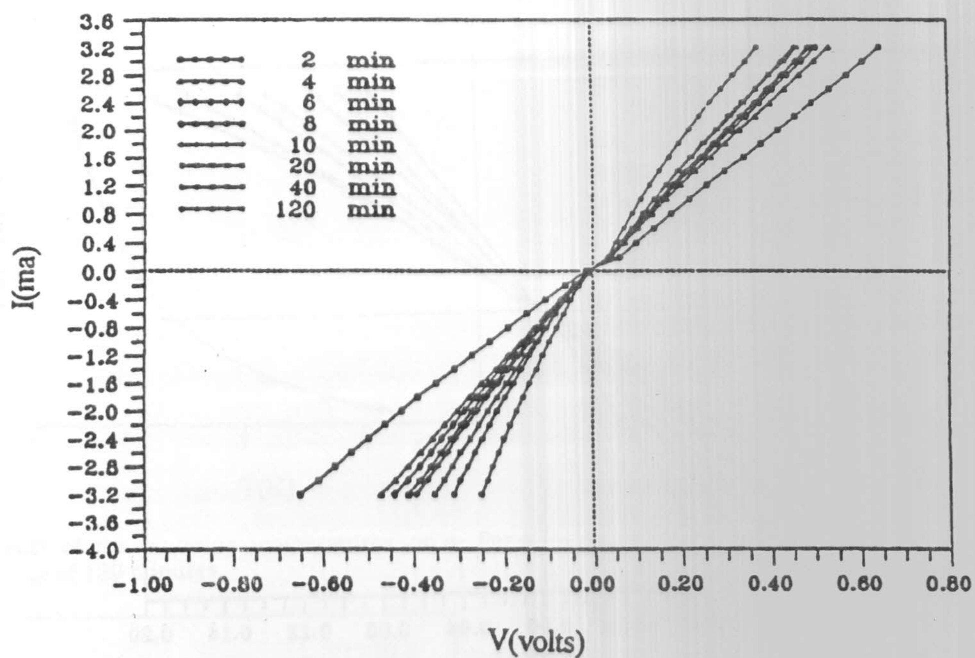

Fig. 3. The I-V characteristics at 673K and different sintering times.

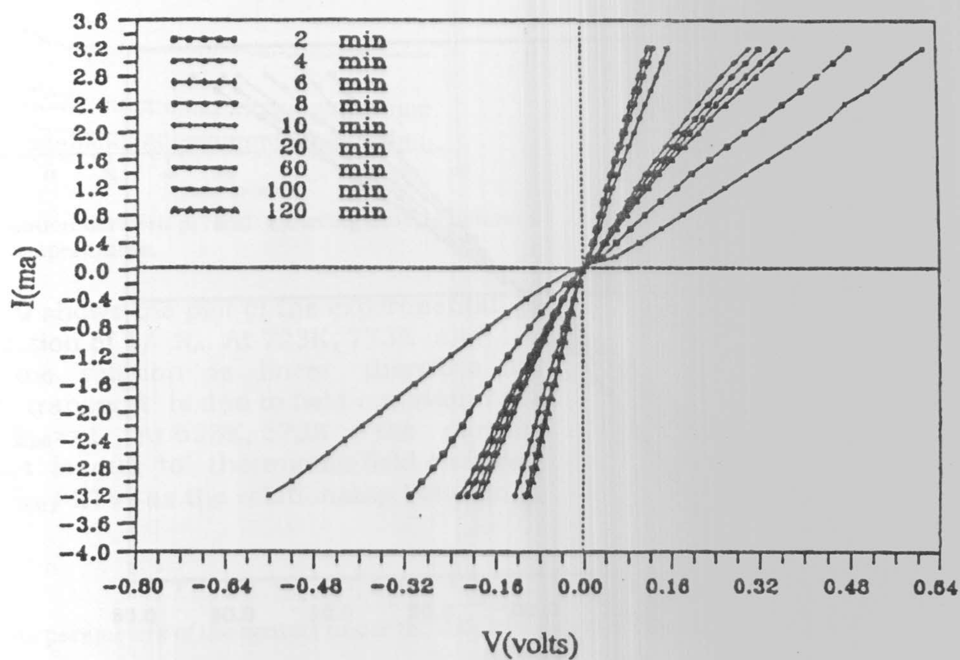

Fig. 4. The I-V characteristics at 723 and different sintering times.

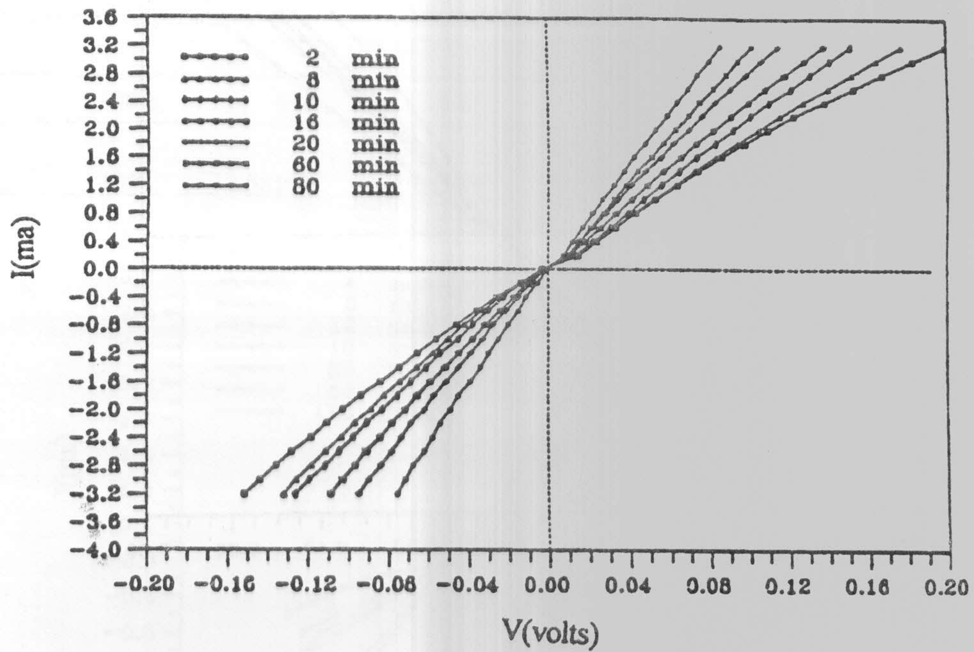

Fig. 5. The I-V characteristics at 773K and different sintering times.

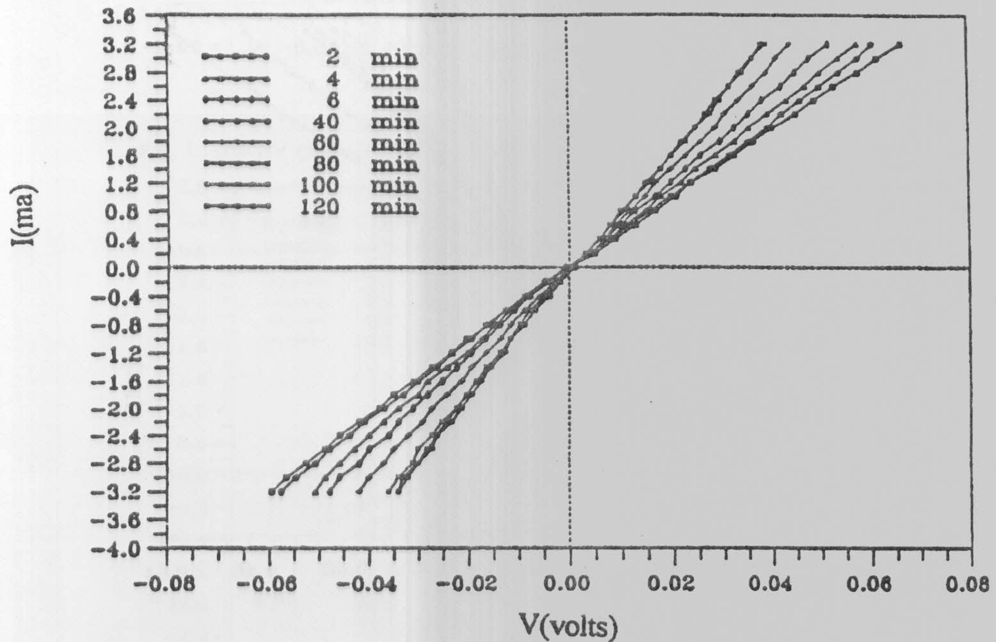

Fig. 6. The I-V characteristics at 823K and different sintering times.

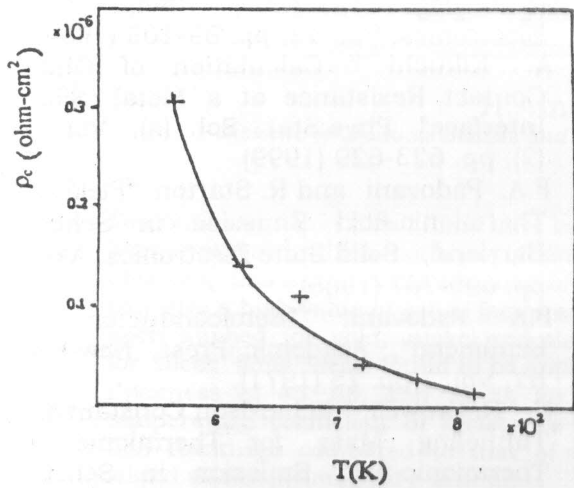

Fig. 7. Effect of the sintering temperatures on ρ_c. For a sintering time of 120 minutes.

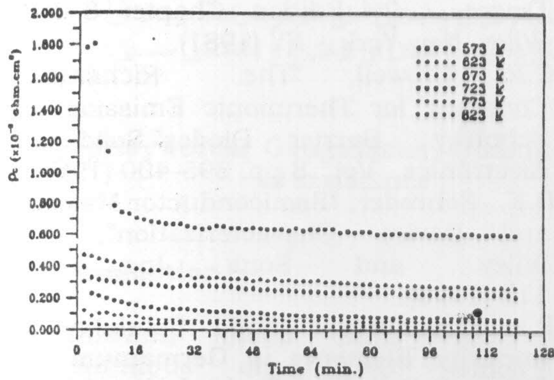

Fig. 8. Relation between ρ_c and sintering time at different sintering temperatures.

Fig. 9 shows the plot of the experimental ρ_c as a function of $1/\ N_A$. At 723K, 773K and 823K, the relation is linear therefore the current transport is due to field-emission with $kT\ /\ E_{00} >> 1$. At 623K, 673K the current transport is due to thermionic-field emission with $E_{00}/\ kT \approx 1$ as the relationship between ρ_c and $1/\sqrt{N_A}$ deviates from linearity. At 573K the current transport is due to thermionic emission with $kT\ /\ E_{00} >> 1$.

Table 2 shows the various parameters of the contact under the different experimental temperatures. The effective tunneling mass m^*_{tun} has been calculated according to [14]. The dielectric constant ε_s has been calculated according to [15]. The different E_{00} values are in agreement with the different type of the conduction mechanisms obtained in Fig. 9. Taking $A^{**}=32\ A/cm^2/K^2$ for p-silicon, the barrier height in the thermionic emission was found to be equal to .36 eV as determined from eq. (4). In the field emission region, ρ_c depends linearly on $1/\sqrt{N_A}$ with a slope equal to $[2\sqrt{\ m^*_{tun}\varepsilon}\ /qh\ ]\ \phi_b$. Table 3 shows the values of ϕ_b in the field-emission region. Fig. 10 shows the effect of the sintering temperature on the barrier height ϕ_b.

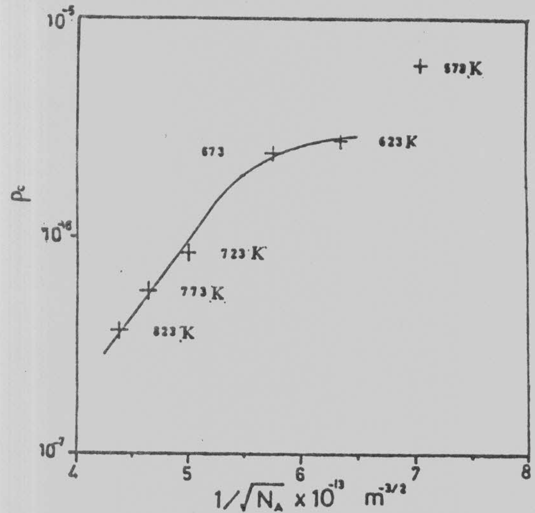

Fig. 9. Experimental relation between ρ_c and $1/\sqrt{N_A}$.

Table 2
The various parameters of the contact under the different experimental temperatures

T (K)	300	573	623	673	723	773	823
$KT/q \times 10^{-2}$	2.58	4.94	5.37	5.8	6.235	6.66	7.09
m^*_{tun}	.8	.9	.92	.95	.97	1	1.2
ε_s	11.7	12	12.5	12.8	13	13.5	13.8
$N_A (m^{-3})$	10^{24}	5×10^{25}	9×10^{25}	10^{26}	1.5×10^{26}	2×10^{26}	2.5×10^{26}
$E_{00} \times 10^{-2}$(ev)	.6	4	5.37	5.8	6.4	7.1	7.22
$m^*_{tun}\varepsilon_s$	9.36	10.8	11.5	12.1	12.6	13.5	16.36
$\rho_c \times 10^{-6}(\Omega)$	.84	.6	.38	.3	.15	.08	.02

Table 3
Values of ϕ_B in the field-emission region at the different temperatures

T (K)	723	773	823
ϕ_b (eV)	0.19	0.102	0.096

5. Conclusions

When this work was carried out we were faced with the fact of definitive measurements of both barrier height and surface doping concentration. A survey on the reported values of the specific resistance shows that its values varies substantially from one report to the other. A problem has been raised. Why? . What are the main factors which affect these values?. In the calculation of the doping concentration it is very difficult to acurately measure the electrical active concentration at the surface, even values taken by the SIMS are often overestimated since not all chemical doping is activated. But by using the proposed interface system, the effect of the different sintering temperatures and sintering times for the AL/P-Si specific contact resistance have been measured at the annealing temperatures. The specific contact resistance decreases from $0.8*10^{-6}$ ohm- cm^2 to $0.01*10^{-6}$ ohm -cm^2 for an increase in the sintering temperature from 573 K to 823 K. The sintering time has no effect on the specific contact resistance.

It is hoped that this study can be used in the future as a guideline in developing ohmic contracts for various semiconductor devices

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