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SPECIFIC CONTACT RESISTANCE OF METAL–SEMICONDUCTOR BARRIERS

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Abstract—The specific contact resistance at zero bias, R_c, serves as a measure of the ohmic or rectifying behavior of a metal–semiconductor barrier under operating conditions. It is thus an important design parameter for semiconductor devices. The values of R_c have been calculated for Metal–Si and metal–GaAs barriers on p-type and n-type samples. The theoretical calculation is based on the generalized transport study of metal-semiconductor systems.

The results, which are presented graphically, show the dependence of R_c on temperature over the range 50°K–500°K, the barrier height from 0.2 to 1.0 eV, and the ionized impurity concentration from 10^{14} to 10^{21} cm^{-3}. Generally R_c decreases exponentially with increasing temperature and with decreasing barrier height. For samples with lower dopings where the thermionic emission dominates, R_c is essentially independent of doping; for higher dopings where the tunneling dominates, R_c decreases rapidly with increasing doping. The experimental results of R_c for various metals on silicon samples are in good agreement with the predictions.

Resumé—La résistance de contact spécifique à polarisation nulle, R_c, sert de mesure du comportement ohmique ou de redressement d'une barriere métal–semiconducteur dans des conditions de fonctionnement. Il est ainsi important en tant que paramètre de conception pour les dispositifs semi conducteurs. Les valeurs de R_c ont été calculées pour les barrières métal–Si et métal–GaAs sur des échantillons du type $-p$ et du type $-n$. Le calcul théorique est fondé sur l'étude de transport généralisé de systèmes métal–semiconducteurs.

Les résultats, présentés graphiquement, montrent la dépendance de R_c sur la température dans la gamme de 50°K à 500°K, la hauteur de barrière entre 0,2 et 1,0 eV, et la concentration d'impureté ionisée entre 10^{14} et 10^{21} cm^{-3}. Généralement R_c diminue exponentiellement avec l'accroissement de température et avec le décroissement de la hauteur de barrière. Pour les échantillons avec doping plus faible où l'émission thermoionique domine, R_c est essentiellement indépendant du doping; pour un doping plus élevé où le tunnellement domine, R_c décroit rapidement à mesure que le doping augmente. Les résultats expérimentaux de R_c pour divers échantillons de métal sur silicium sont en bon accord avec les prévisions.

Zusammenfassung—Bei einem Halbleiter-Metall-Kontakt unter Betriebsbedingungen dient der spezifische Kontaktwiderstand R_c ohne Vorspannung als Maß für ohmsches Verhalten oder Gleichrichterwirkung. Er ist daher eine wichtige Größe bei der Konstruktion von Halbleiterbauelementen. Die Werte für R_c wurden für Metall-Silizium- und Metall-Galliumarsenid-Barrieren mit p- oder n-Typ Kristallen berechnet. Die theoretische Rechnung beruht auf einer verallgemeinerten Studie der Transporteigenschaften eines Metall-Halbleiter-Systems.

Die graphisch wiedergegebenen Ergebnisse zeigen den Verlauf von R_c für einen Temperaturbereich von 50°K bis 500°K, Barrierenhöhen zwischen 0,2 und 1,0 eV und Konzentrationswerte der ionisierten Störstellen von 10^{14}/cm^3 bis 10^{21}/cm^{-3}. Ganz allgemein nimmt R_c mit der Temperatur ab und mit der Barrierenhöhe zu. Bei Proben mit niedrigerer Dotierung, wo die thermische Emission überwiegt, ist R_c im wesentlichen von der Konzentration unabhängig. Mit höherer Dotierung nimmt R_c rasch wegen des überwiegenden Tunnelstromes ab. Die experimentellen Ergebnisse für R_c mit verschiedenen Metallen auf Silizium sind in guter Übereinstimmung mit den vorhergesagten Werten.

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1. INTRODUCTION

THE SPECIFIC contact resistance is defined as the reciprocal of the derivative of current density with respect to voltage. When evaluated at zero bias, this specific contact resistance, R_c, is an important figure of merit for the transport characteristic of a metal–semiconductor barrier. For example, for a good ohmic contact,[1] it is required that the value of R_c should be sufficiently small so that the observed linear current–voltage characteristic is mainly due to the series resistance of the semiconductor material near the contact.

Based on the generalized majority-carrier transport theory[2], we shall obtain the specific contact resistance for metal–Si and metal–GaAs barriers on p-type and n-type samples. For a given semiconductor, the value of R_c depends on the temperature, the barrier height, and the impurity concentration. We shall present in graphical form the values of R_c over practical ranges of these parameters. These results are useful in designing and characterizing many semiconductor devices operated at various current and temperature ranges.

The basic transport equation of a metal–semiconductor system is presented in Section 2. The expressions for the specific contact resistance and its thermal coefficient are derived in Section 3; while the computed results are given in Section 4. A summary is presented in Section 5.

2. BASIC TRANSPORT EQUATION

The energy band diagram of a metal–semiconductor barrier under equilibrium conditions is shown in Fig. 1 where $\Delta\varphi$ is the barrier lowering due to image force, φ_B is the barrier height, and V_{b0} is the built-in potential. The energy ξ is measured upward from the barrier maximum which is used as a reference, while η is measured downward from the reference. (Both $\Delta\varphi$ and φ_B are dependent on the applied voltage.)

The basic transport equation in a metal-semiconductor barrier is given by [2]

$$J = J_{SM} - J_{MS} \tag{1}$$

where J is the total current density, J_{SM} is the current density flowing from the semiconductor to the metal, and J_{MS} is the corresponding current density flowing from the metal to the semiconductor.

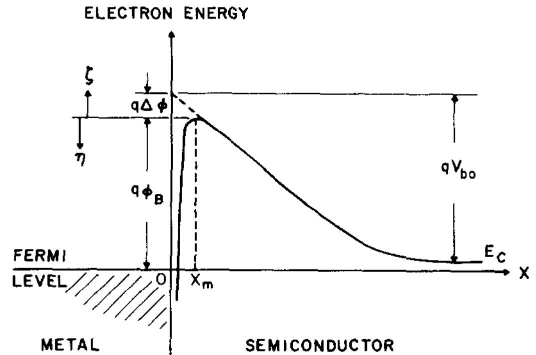

Fig. 1. Energy band diagram of a metal–semiconductor contact at thermal equilibrium.

The expression for J_{SM} at a bias voltage V is given by

$$J_{SM}(V) = \frac{A^*T}{k}\int_0^\infty P(\xi)e^{-(q\varphi_B - qV + \xi)/kT}\mathrm{d}\xi + \frac{A^*T}{k}\int_0^{q(V_{b0}-V-\Delta\varphi)} F_S P(\eta)(1-F_m)\mathrm{d}\eta \tag{2}$$

where A^* is the effective Richardson constant, and F_S and F_m are the Fermi–Dirac distribution functions in the semiconductor and in the metal respectively. $P(\xi)$ and $P(\eta)$ are the quantum transmission functions above and below the barrier maximum respectively. The first term on the right-hand of equation (2) represents the contribution from thermionic emission of carriers over the barrier maximum. The second term is the tunneling component. The expression for the other current density J_{MS} is essentially the same as that given by equation (2) except that the exponential term is replaced by $\exp[-(q\varphi_B + \xi)/kT]$. The relative magnitude of the thermionic emission and tunneling components depends on the barrier height, temperature, and doping concentration which is implicit in the transmission functions. For degenerate semiconductors, the product of distribution functions, $F_S(1-F_m)$ in equation (2) is replaced [3] by $\ln\{1+\exp[(E-E_F)/kT]\}$, where E_F is the Fermi level.

3. SPECIFIC CONTACT RESISTANCE

As mentioned previously, the specific contact

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resistance is defined as

$$R_c \equiv \left(\frac{\partial J}{\partial V}\right)^{-1}_{V=0}. \quad (3)$$

Since the accurate quantum transmission functions have to be obtained by numerical analysis, it is difficult to express J and R_c in closed forms. We shall, however, consider two limiting cases so that a clear physical picture can be obtained for R_c. The exact calculations of R_c will be presented in Section 4.

3.1. *Thermionic emission*. For samples of lower doping concentrations the thermionic-emission component dominates the current transport so that the second term in equation (2) can be neglected. If we assume that the transmission function is unity, we can obtain the standard Richardson expression for the current density J_{SM}:

$$J_{SM} = J_S e^{qV/kT} \quad (4)$$

where J_S is the saturation current density given by

$$J_s = A^* T^2 e^{-q\varphi_B/kT}. \quad (4a)$$

The total current density is then

$$J = J_{SM} - J_{MS} = J_S(e^{qV/kT} - 1). \quad (5)$$

From equations (3), (4a) and (5), the specific contact resistance is given as

$$R_c = \frac{k}{qA^*T} e^{q\varphi_B/kT} = \frac{kT}{qJ_S}. \quad (6)$$

In deriving equation (6) we have neglected the small voltage dependence of the barrier height.

The thermal coefficient of R_c is defined as

$$\gamma \equiv -\frac{1}{R_c}\frac{\partial R_c}{\partial T} = (1 + q\varphi_B/kT)/T. \quad (7)$$

It is clear from equation (6) that R_c will decrease exponentially with increasing temperature and with decreasing barrier height. The value of R_c will be inversely proportional to the effective Richardson constant; this means that R_c will decrease with increasing effective mass for the cases where the thermionic emission dominates. From equation (7) we note that the thermal coefficient will also decrease with increasing temperature and with decreasing barrier height.

3.2 *Tunneling*. For samples of higher doping concentrations, the tunneling process may dominate, and we can neglect the first term in equation (2). If we use the WKB approximation for the transmission function we obtain [3, 4]

$$P(\eta) = \exp\left[-q(V_{bo} - V)/E_{00}\right] \quad (8)$$

where

$$E_{00} = \frac{\hbar}{2}\sqrt{\left(\frac{N}{\epsilon_S m^*}\right)}.$$

The quantity E_{00} is a reference energy which depends on the doping N, the semiconductor permittivity ϵ_S, and the effective mass m^*.

Substitution of equation (8) into equations (2) and (3) yields

$$R_c \sim \left(\frac{1}{E_{00}}\right)\exp\left(qV_{bo}/E_{00}\right). \quad (9)$$

From equation (9) it is clear that in the tunneling range the specific contact resistance is independent of temperature (or $\gamma \ll 1$). Equation (9) indicates that for the tunneling case, R_c depends strongly on the the doping concentration and the tunneling effective mass, and decreases exponentially with the factor $\sqrt{(N/m^*)}$.

4. RESULTS

To calculate the specific contact resistance, R_c, and its thermal coefficient, γ, we use the pertinent Richardson constant [5] A^*, the tunneling effective mass, [6] and the dynamic dielectric constant [7] corresponding to the carrier transit time from the metal-semiconductor interface to the potential maximum (from $x = 0$ to $x = x_m$ as shown in Fig. 1). Table 1 lists the room-temperature values of the effective Richardson constants and dielectric constants for various silicon and GaAs metal-semiconductor systems.

In silicon the tunneling effective mass which is a strong function of temperature and doping concentration, can be expressed as

$$m^* = \left[l^2/m_l + (m^2 + n^2)/\sqrt{(m_d^3/m_l)}\right]^{-1} \quad (10)$$

where l, m, and n are the directional cosines of carrier transport with respect to the main axis of

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Table 1. Effective Richardson constant and dielectric constant at 300°K

Semiconductor	Type	Orientation	A^* (amp/cm^2°K)	ϵ_S/ϵ_0
Si	n	⟨111⟩	270	12
		⟨100⟩	200	
	p	—	79	
GaAs	n	—	8	11
	p	—	74	

one valley, m_l is the longitudinal effective mass, and m_d is the density of state effective mass. From the measured results[6, 8] of m_d and m_l, the value of the tunneling effective mass can be determined from equation (10) and is shown in Fig. 2 as a function of temperature and doping concentration for n-type, ⟨111⟩ oriented silicon. For dopings lower than 5×10^{17} cm^{-3}, the mass m^* is essentially the same as that of 5×10^{17} cm^{-3}. For higher dopings, however, m^* increases with the doping.

For GaAs the dependence of the tunneling effective mass on temperature and doping concentration is still under investigation[9], we shall assume that the tunneling effective mass has its low-temperature value, i.e. 0.068 m_0 for electrons and 0.12 m_0 for holes where m_0 is the free electron mass.

Figure 3 shows the theoretical R_c at room temperature for n-type (solid lines) and p-type (dotted lines), ⟨111⟩-oriented silicon samples of various doping concentrations and barrier heights. For a given doping concentration, R_c decreases with decreasing φ_B; and for a given φ_B, R_c decreases with increasing N. These results are consistent with equations (6) and (9). Also shown in Fig. 3 are some experimental results of Al–Si ($\varphi_B \simeq 0.6$V), [10] Mo-Si ($\varphi_B \simeq 0.6$V),[10] and PtSi–Si ($\varphi_B \simeq 0.85$V)[2] barriers. It is apparent that the agreement between theory and experiment is reasonably good. Similar results for GaAs samples are shown in Fig. 4. The general features are the same as Fig. 3. However, in the tunneling range, R_c for GaAs is smaller because of its smaller effective mass.

From these figures, it is clear that to obtain a given R_c (e.g. for a contact of 10^{-4} Ω-cm^2 in silicon) we can either use a heavily doped sample with a relatively high barrier height (say $N = 4\times10^{19}$ cm^{-3} for $\varphi_B = 0.8$V) or a lightly doped sample with a lower barrier height (say $N = 3\times10^{18}$ cm^{-3} for $\varphi_B = 0.4$V). Table 2 lists some values of R_c for PtSi–Si contacts formed on ⟨111⟩ oriented n-type silicon.

Table 2. R_c for PtSi–Si *contacts ($\varphi_B = 0{\cdot}85$ V) on ⟨111⟩ oriented n-type silicon*

R_c(Ω-cm^2) T / N_D(cm^{-3})	200°K	300°K	400°K
10^{16}	5×10^{11}	2×10^{5}	20
10^{17}	2×10^{11}	10^{5}	10
10^{18}	2×10^{9}	10^{4}	6
10^{19}	10	1	0.5
10^{20}	10^{-5}	10^{-5}	2×10^{-5}

The results of temperature dependence of R_c for various samples are shown in Figs. 5–8 where the doping concentration and barrier height are used as parameters. We note that in the thermionic emission range ($10^{14} \sim 10^{17}$ cm^{-3}), R_c is essentially independent of doping concentration. This is consistent with equation (6). In the tunneling range ($>10^{18}$ cm^{-3}), however, R_c becomes a strong function of doping. It is also interesting to note that a good rectifying contact (large R_c) at lower temperatures may become a good ohmic contact (small R_c) when the operating temperature is increased. Hence, for high-power elevated-temperature operation, the high-temperature values of R_c should be used in the device design theory.

The thermal coefficients of R_c are shown in Figs. 9 and 10 for n-type silicon and n-type GaAs respectively. Similar results can be obtained for p-type samples. We note that the general feature

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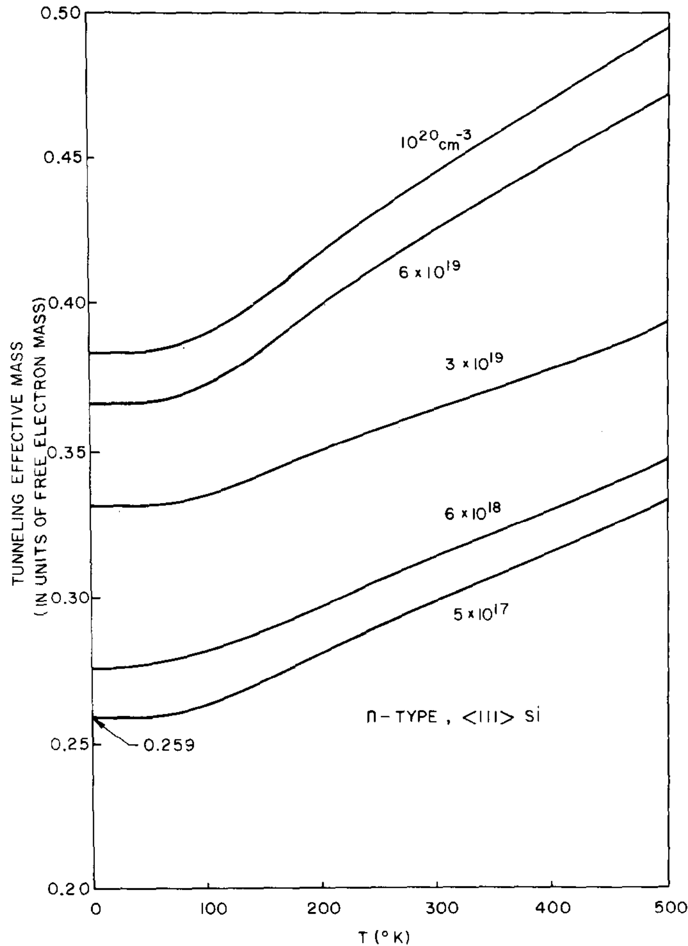

Fig. 2. Tunneling effective mass as a function of temperature and doping concentration for n-type, $\langle 111 \rangle$ oriented silicon.

of the temperature dependence of γ follows equation (7), i.e. γ decreases with decreasing φ_B and increasing T. To obtain low thermal coefficient of R_c, we should use samples of low barrier height and large doping concentration. For Si samples, γ changes sign at 3×10^{19} cm^{-3}, causing a discontinuity in $\ln \gamma$ as shown in Fig. 9. This is mainly due to the effect of the tunneling effective mass which increases with doping as shown in Fig. 2.

5. SUMMARY

The dependence of the specific contact resistance, R_c, on various parameters can be summarized as follows:

(1) Ionized impurity concentration: As the concentration increases, the depletion width becomes narrower, which in turn causes the transmission coefficient for tunneling to increase. Thus, even a high barrier contact can become ohmic if the barrier is thin enough such that tunneling dominates the carrier transport process (as can be seen in Figs. 3 and 4). Because of the statistical nature of impurity distribution in the samples, as the impurity concentration increases, it is expecred that the saturation current density will become larger than the value calculated for the average concentration[2]. This in turn will cause some reduction of R_c.

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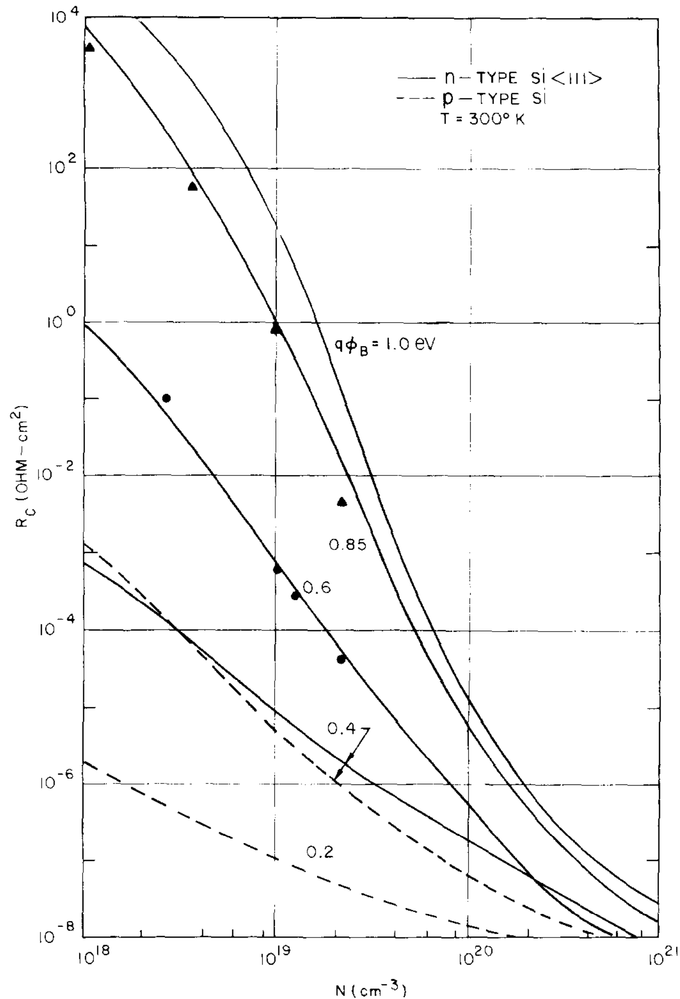

Fig. 3. Theoretical specific contact resistance at 300°K for n-type, ⟨111⟩ oriented (solid lines) and p-type (dotted lines) silicon. The solid circles are experimental results of Al–Si and Mo–Si barriers ($q\varphi_B = 0.6$ eV), and triangles for PtSi–Si barriers ($q\varphi_B = 0.85$ eV).

(2) Temperature: The temperature effect arises from the distribution functions. For higher temperatures more carriers are excited above the Fermi level. The current density is increased, causing a decrease in R_c as shown in Figs. 5–8.

(3) Barrier height: As the barrier height decreases, both the thermionic emission component and the transmission coefficient increase. There is a large number of carriers which can transport from the semiconductor band edges to the metal and vice versa. The contact resistance will be low. However, as the doping increases, the barrier height will become less important (referring to Figs. 3 and 4 where all curves converge at high doping limits).

(4) Effective Richardson constant: This constant generally depends on the crystal orientation (e.g. for Si) and can modulate the magnitude of the carrier transport mechanism. In the high temperature region, the phonon scattering effect[11]

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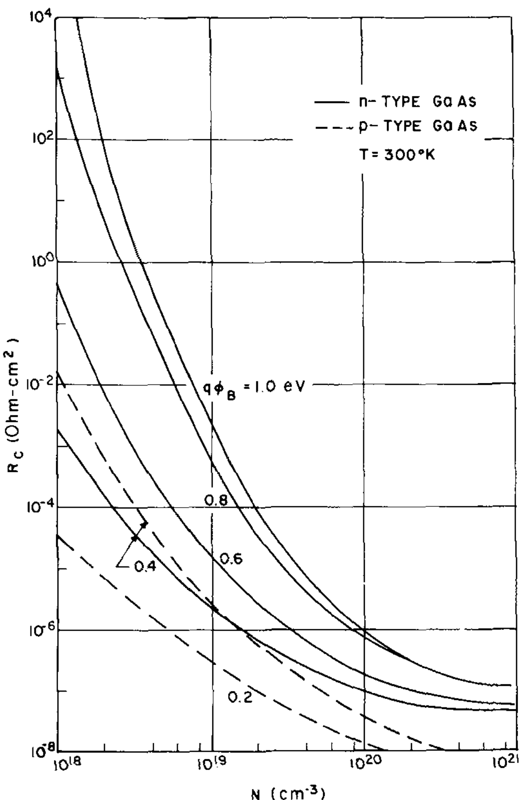

Fig. 4. Specific contact resistance at 300°K for n-type and p-type GaAs.

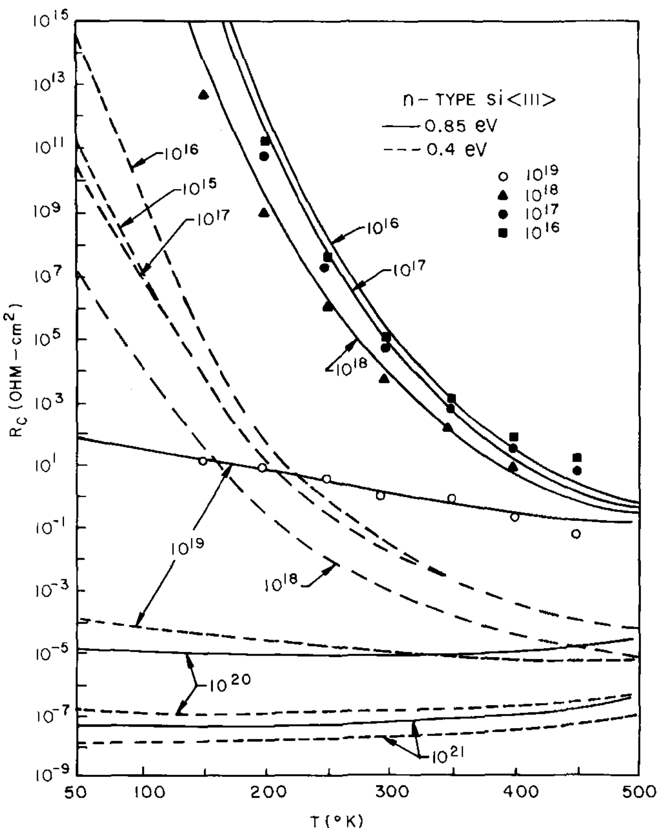

Fig. 5. Specific contact resistance for n-type ⟨111⟩ Si samples vs. temperature. Barrier height and doping concentration are parameters. Also shown are experimental results of PtSi–Si barriers made on silicon substrates of various dopings.

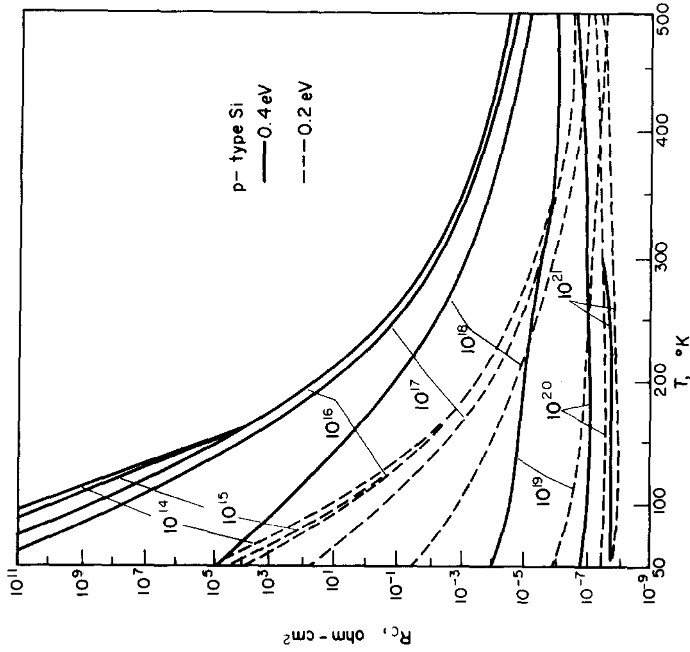

Fig. 7. Specific contact resistance for p-type Si samples.

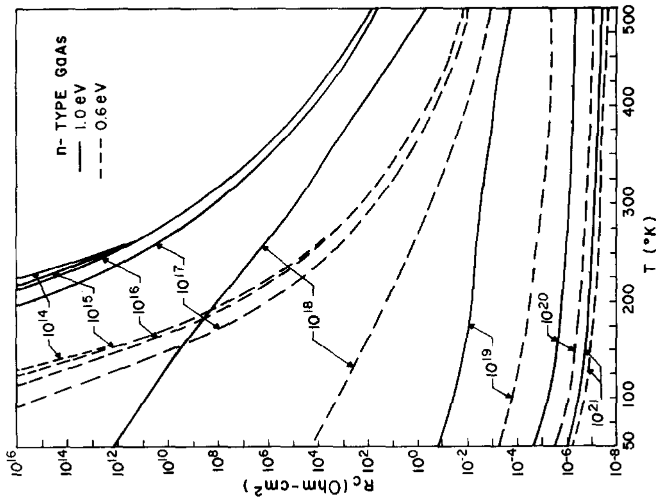

Fig. 6. Specific contact resistance for n-type GaAs samples vs. temperature. Barrier height and doping are parameters.

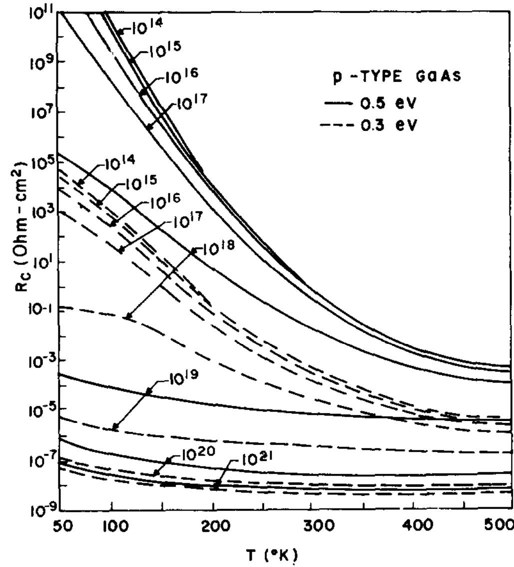

Fig. 8. Specific contact resistance for p-type GaAs samples.

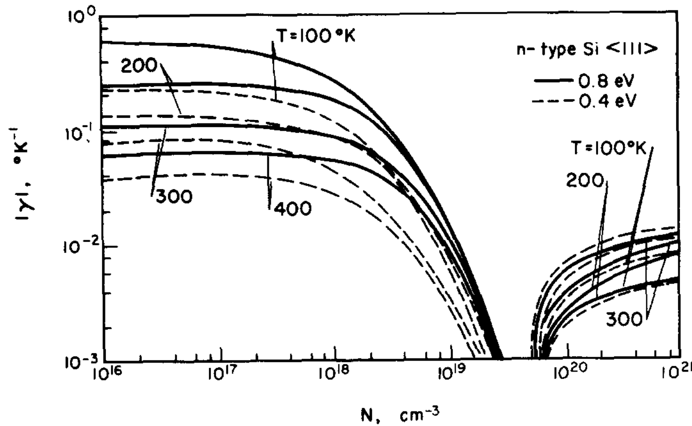

Fig. 9. Thermal coefficient vs. doping concentration for n-type, ⟨111⟩ Si samples.

will slightly reduce the value of A^*. However, A^* has relatively small effect on R_c in comparison with the barrier height or the impurity concentration.

(5) Tunneling effective mass: Small effective mass will give rise to large transmission coefficient. small values of R_c can be obtained for materials with small tunneling effective mass. The mass depends upon the direction of carrier transport if the band extrema do not occur at the center of the Brillouin zone and when the constant energy surface is not spherical. For n-type Si in the ⟨100⟩ direction the low-temperature tunneling effective mass is 0.1905 m_0 which is smaller than that for ⟨111⟩-oriented samples. The values of R_c for n-type ⟨100⟩-oriented Si are about a factor of two lower than that shown in Fig. 3. For a given doping,

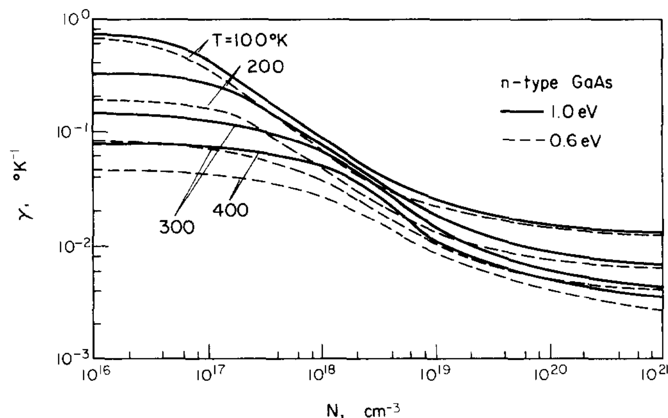

Fig. 10. Thermal coefficient vs. doping concentration for *n*-type GaAs samples.

the tunneling effective mass is a function of temperature. This may cause the specific contact resistance to increase slightly at higher temperatures (e.g. for dopings of 10^{20} and 10^{21} cm^{-3} in Figs. 5 and 7).

The results of R_c which are presented in Figs. 3–8 cover the practical ranges of temperature, doping, and barrier height. These results are believed to be useful in design theory of many semiconductor devices.

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