

F-5-4

Minimum Value of the Specific Contact Resistance of Si-Metal Contacts —The Origin and the Magnitude—

Kenji Natori, Tomo Shimizu and Nobuyuki Sano

Institute of Applied Physics, University of Tsukuba
Tsukuba, Ibaraki 305-8673, Japan

Phone:+81-298-53-5311 Fax:+81-298-53-5205 Email: natori@hermes.esys.tsukuba.ac.jp

1. Introduction.

The scaling law predicts that the resistance of Si-metal contacts rapidly increases in proportion to inverse of the squared device scaling ratio. The suppression of the increase is one of the most serious problems for future ULSIs. In 2010, the specific contact resistance R_c [Ωcm^2], which is the contact resistance per unit area, is required to be around 10^{-8} Ωcm^2 according to the road map. However, the conventional analysis (e.g. [1][2]) does not clearly indicate how small it can be and what mechanism regulates the minimum value.

This paper discusses the contact resistance from a novel point of view, and indicates that the minimum possible value of the Si-metal specific contact resistance is around 10^{-10} Ωcm^2 with discussion on mechanism that dominates the minimum value for the first time.

2. Analysis.

In order to estimate the magnitude of current through Si-metal contact, which is illustrated in Fig. 1, we apply the Landauer's formula approach. As is shown in Fig. 2, carriers flow from the bulk Si (metal) across a very thin interface layer to the bulk metal (Si). Since the carrier density-of-state in metal is far larger than that in Si, the carrier current is approximated as is shown in Eq. (1) of Fig. 3. Current flow is assumed along x_1 -axis (interface is in x_2 - x_3 plane perpendicular to x_1 -axis). The carrier flux from Si to metal, for example, is the product of the carrier velocity v_1 along x_1 -axis, the carrier transmission probability T through the thin interface layer, and the difference of metal and Si Fermi functions f_s and f_m , respectively, all summed up over the initial Si states.

The transmission probability T represents the transport through the interface, and reflects every effect of interface including the geometrical and energetic structure around there. The value of T continually distributes from 0 to 1. The present day T for Si-metal contact is far smaller than its maximum value of unity. The future interface engineering technique will improve this value toward unity, hopefully to a value slightly less than unity. Thus the minimum value of the contact resistance should be evaluated by putting $T=1$.

3. Results.

Eq. 1 yields the expression of $R_{c\text{min}}$, the minimum of R_c , shown in Eq. 2 of Fig. 3, which is convenient for numerical evaluation of $R_{c\text{min}}$ when a specific energy-momentum (E - k) relation is given. h is the Planck constant, and a common Fermi function f is used. For a contact on (100) surface of n-Si, the constant energy surface of carriers in Si consists of six ellipsoids and $R_{c\text{min}}$ is analytically calculated as in Eq. (3)

of Fig. 3. Here, kT is the thermal energy, m_t and m_l respectively give the transverse and the longitudinal electron effective mass of Si, and $\mu_e=(E_f-E_c)$ is the Si Fermi energy with respect to the conduction band minimum.

When carriers are fully degenerate in a highly doped Si and have a Fermi surface just like those in metals ($\mu_e \gg kT$), Eq. (1) leads to $R_{c\text{min}}$ of the form Eq. (4) of Fig. 3, that is, the contact resistance minimum is inversely proportional to the projected area of the Fermi surface. In case the Fermi surface is a sphere as is shown in Fig. 4, we obtain $R_{c\text{min}}=h^3/(4\pi m_e^2 \mu_e)$. For a contact on (100) surface n-Si, $R_{c\text{min}}$ is reduced to Eq. (5) of Fig. 3. Notice that $R_{c\text{min}}$ is inversely proportional to μ_e in both cases.

The mechanism that regulates $R_{c\text{min}}$ is argued as follows. When the interface layer is transparent for electron transport, the contact resistance is controlled by the number of carriers that are incident from bulk Si to the interface. When the Si is highly doped and the carrier is degenerate, the number of the carrier is regulated by the density of states of the bulk Si Fermi surface as is derived in Eq. (4). But when non-degenerate due to low doping, the number is dominated by the doping concentration itself. The contact resistance is a property related to the interface, but we know that the minimum value is regulated by the bulk Si property irrespective of the interface structure.

Values of $R_{c\text{min}}$ for the n-Si and the p-Si contacts are numerically calculated considering the conduction band minimum, as well as the complex structure of the valence band maximum of Si, and are respectively shown in Fig. 5 and Fig. 6. For low doping concentration of Si, the specific contact resistance exponentially decreases as the Fermi energy increases. In high concentration, it is inversely proportional to μ_e and so the (2/3) order of the carrier concentration (electron concentration N_e or hole concentration N_h), and one can see that the minimum value is around 10^{-10} Ωcm^2 in view of the impurity solid solubility. Note that n-Si contact has a slightly smaller $R_{c\text{min}}$ value. As for the temperature dependence, $R_{c\text{min}}$ value strongly depends on T when carriers are not degenerate, but it becomes temperature independent in the carrier degeneracy.

4. Conclusion

The specific contact resistance of Si-metal junction has a minimum regulated by the density of states of bulk Si, and the magnitude of the minimum value is around 10^{-10} Ωcm^2 .

References

- [1] A. Y. C. Yu, Solid-State Electronics, **13**, 239 (1970).
- [2] C. Y. Chang, Y. K. Fang and S. M. Sze, Solid-State

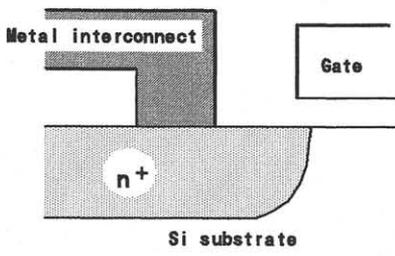


Fig. 1. The cross section of the Si-metal contact

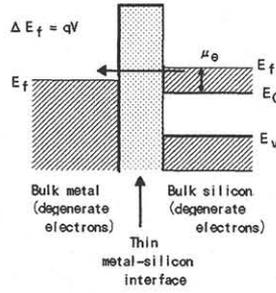


Fig. 2. Carriers flow from bulk Si through a very thin interface layer to bulk metal.

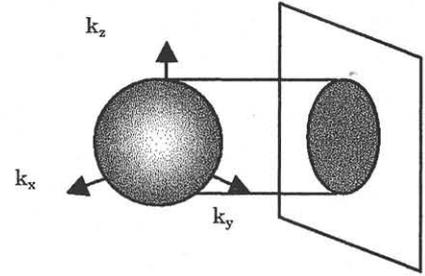


Fig. 4. Projected area of the spherical Fermi surfaces.

$$I = 2e \sum_{\text{valley}} \sum_{k_2, k_3} \sum_{k_1} v_1 T(f_s - f_m) \quad (1)$$

$$R_{c \min} = \left[\frac{1}{(2\pi)^2} \frac{2e^2}{\hbar kT} \sum_{\text{valley}} \int_{-\infty}^{\infty} dk_2 \int_{-\infty}^{\infty} dk_3 \int_{\frac{\partial E}{\partial k_1} \geq 0} dk_1 \frac{\partial E}{\partial k_1} f(1-f) \right]^{-1} \quad (2)$$

$$R_{c \min} = \left[\frac{4\pi e^2 kT}{h^3} (2m_t + 4\sqrt{m_t m_l}) \ln \left\{ 1 + \exp\left(\frac{\mu_e}{kT}\right) \right\} \right]^{-1} \quad (3) \quad R_{c \min} = \frac{1}{(2\pi)^2} \frac{2e^2}{h} \sum_{\text{valley}} (\text{projected area of Fermi surface}) \quad (4)$$

$$R_{c \min} = \left[\frac{4\pi e^2}{h^3} (2m_t + 4\sqrt{m_t m_l}) \mu_e \right]^{-1} = \left[\left(\frac{\pi}{4}\right)^{1/3} \frac{e^2}{h} \left(\frac{m_t}{m_l}\right)^{1/3} + 2 \left(\frac{m_l}{m_t}\right)^{1/6} \right]^{-1} N_e^{-2/3} \quad (5)$$

Fig. 3. Derived formulae. (1) Current through the Si-metal contact. (2) Specific contact resistance minimum $R_{c \min}$. (3) $R_{c \min}$ of n-Si-metal contacts. (4) General expression of $R_{c \min}$ at $T=0$. (5) $R_{c \min}$ of n-Si-metal contacts at $T=0$.

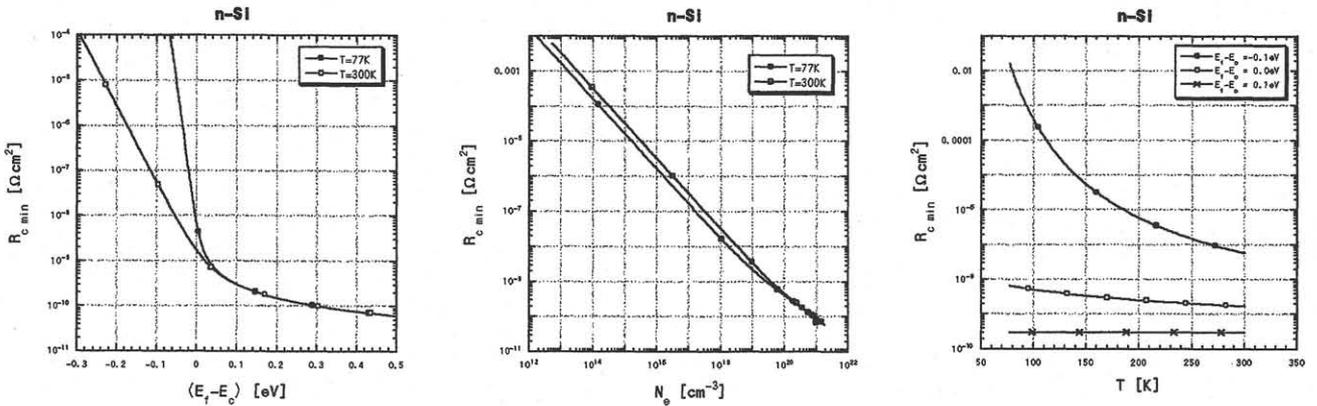


Fig. 5. Minimum resistance of n-Si-metal contacts. $R_{c \min}-(E_f - E_c)$, $R_{c \min}-N_e$ (electron concentration) and $R_{c \min}-T$ relationship.

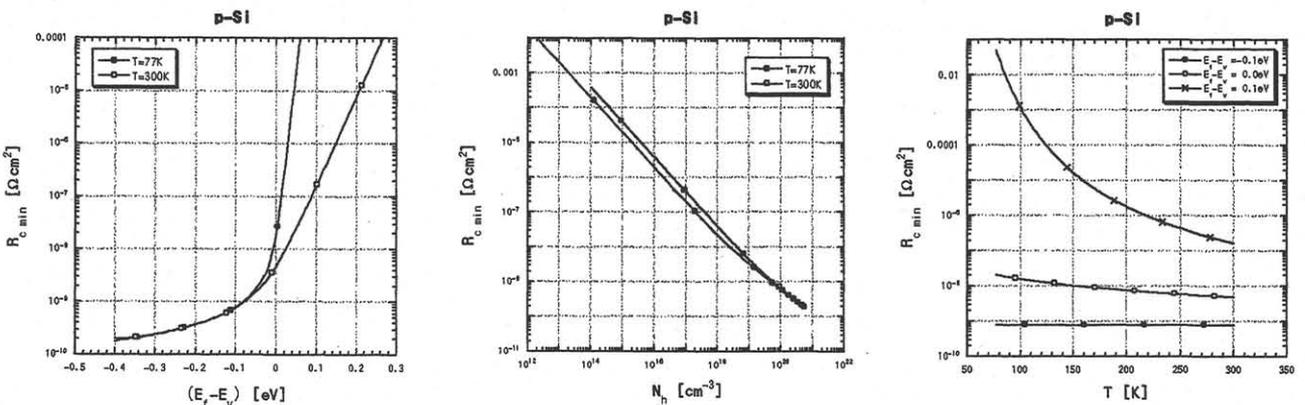


Fig. 6. Minimum resistance of p-Si-metal contacts. $R_{c \min}-(E_f - E_v)$, $R_{c \min}-N_h$ (hole concentration) and $R_{c \min}-T$ relationship.