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CURRENT–VOLTAGE CHARACTERISTICS OF A CONTACT SYSTEM BASED ON AN ION-IMPLANTED $NiSi_2$ ULTRATHIN FILM FORMED ON Si(111)

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Mustafoyeva Nodira Moyliyevna[1]
Mustafayeva Nilufar Moyli qizi[2]
[1]*Professor at the Academy of the Ministry of Emergency Situations, Tashkent city, Uzbekistan*
[2]*Senior Lecturer, Academy of the Ministry of Emergency Situations, Tashkent city, Uzbekistan*

Abstract: *This paper analyzes the electrical properties of a Ni/$NiSi_2$/Si(111)/Ni contact system incorporating an ultrathin $NiSi_2$ layer formed by Ni^+ ion implantation followed by thermal annealing. According to the data reported in the author's PhD dissertation and monograph, a $NiSi_2$ layer with a thickness of 30–40 Å (3–4 nm) was formed by annealing at approximately 900 K, and a 0.3 μm-thick Ni layer was used as the contact electrode. The current–voltage (I–V) characteristic of the system is nearly linear under both forward and reverse bias. The curves recorded in the dark and under illumination at 4300 lx are close to one another within the resolution of the reproduced graph. The reported resistivity of the $NiSi_2$ layer is 4×10^{-5} Ω·cm, while the Schottky barrier height at the $NiSi_2$/Si(111) interface is 0.63 eV. The total resistance, estimated approximately from the original graph, is about 10 kΩ. The contact properties were reported to remain practically unchanged up to approximately 700 K. These findings indicate the potential of $NiSi_2$ ultrathin films for use in silicon-based contact systems.*

Keywords: *$NiSi_2$; Si(111); ultrathin film; ion implantation; thermal annealing; current–voltage characteristic; ohmic contact; Schottky barrier; electrical resistivity.*

1. INTRODUCTION

The electrical properties of metal–semiconductor contacts in silicon-based microelectronic and nanoelectronic devices are among the factors that determine device performance, power losses, and thermal stability. Low contact resistance, reproducible current–voltage behaviour, and retention of electrical parameters under temperature variations are therefore of practical importance.

Nickel disilicide ($NiSi_2$) is an important material for the study of silicide–silicon contacts because it can form an epitaxial interface with silicon and exhibits low electrical resistivity. At the same time, charge transport across the $NiSi_2$/Si interface depends on crystallographic orientation, the atomic

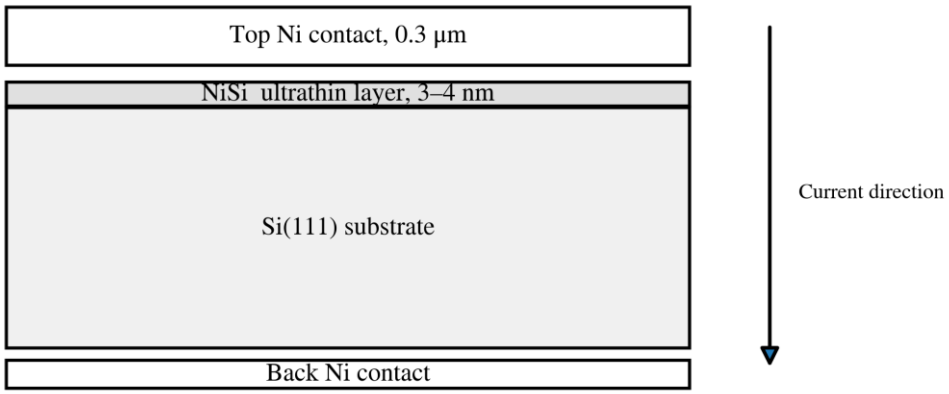
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structure of the interface, the doping level of the substrate, and surface-preparation conditions. Tung et al. showed that the Schottky barrier height at the $NiSi_2$/Si(111) interface is sensitive to surface-preparation conditions [3]. Parui et al. reported rectifying Schottky behaviour and variations in local barrier values at epitaxial $NiSi_2$/n-Si(111) interfaces [4].

The aim of this paper is to re-examine the current–voltage characteristic of a contact system incorporating a $NiSi_2$ ultrathin film, using results obtained in the author's earlier studies; to evaluate its electrical parameters; and to discuss the reported linear I–V response and the Schottky barrier at the interface within a consistent physical framework.

2. Sample Preparation and Experimental Methodology

The system under consideration was formed by implanting Ni^+ ions into the Si(111) surface, followed by thermal annealing. The PhD dissertation reports the formation of a $NiSi_2$ layer with a thickness of approximately 30–40 Å after annealing at about 900 K [1]. A 0.3 μm-thick Ni layer was deposited on the $NiSi_2$/Si(111) surface as the contact metal. This procedure produced a Ni/$NiSi_2$/Si(111)/Ni contact system.



Ni / NiSi / Si(111) / Ni contact system

Schematic illustration; layer thicknesses are not to scale

Figure 1. Schematic cross-section of the Ni/$NiSi_2$/Si(111)/Ni contact system (not to scale).

The electrical characteristic was recorded under forward and reverse bias, both in the dark and under illumination at 4300 lx. The source reports that the I–V curves are nearly linear and that the contact quality remains practically unchanged after heating the system to approximately 700 K [1, 2].

In the linear region, the effective resistance is determined from the ratio of the changes in voltage and current:

$$R_{eff}=\Delta U/\Delta I \quad (1)$$

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The electrical conductance is the reciprocal of the effective resistance:

$$G = \frac{\Delta I}{\Delta U} = \frac{1}{R_{eff}} \quad (2)$$

If the layer geometry and the cross-section through which the current flows are known, the resistivity can be expressed as:

$$\rho = R\frac{S}{L} \quad (3)$$

Here, S is the cross-sectional area perpendicular to the current direction, and L is the length along the current path. For thin films, the geometry of the four-probe measurement and the lateral dimensions of the layer must be taken into account. Consequently, the resistivity of the film cannot be calculated directly from the total resistance of the complete contact system.

3. Experimental Results and Their Analysis

3.1. Electrical Parameters of the $NiSi_2$/Si(111) System

The tabulated data reported in the author's PhD dissertation and monograph are summarized in Table 1 [1, 2].

Parameter	Value reported in the source	Comment
$NiSi_2$ layer thickness	30–40 Å (3–4 nm)	After ion implantation and thermal annealing
Thickness of the Ni contact layer	0.3 μm	Top contact metal layer
Resistivity of Si(111)	10 Ω·cm	The source table specifies p-type Si, Np = 10^{17} cm^{-3}
Resistivity of $NiSi_2$	4×10^{-5} Ω·cm	Value listed in the source table
Schottky barrier at $NiSi_2$/Si(111)	0.63 eV	Interface parameter reported in the source
Thermal stability of the contact	Up to approximately 700 K	Contact quality reported to remain practically unchanged

Table 1. Main parameters reported for the $NiSi_2$/Si(111) contact system.

The resistivity of the $NiSi_2$ layer is several orders of magnitude lower than the value reported for the silicon substrate. This difference indicates the role of the $NiSi_2$ layer as a conducting contact layer. However, the value of 4×10^{-5} Ω·cm represents the resistivity of the layer and should not be equated with the total resistance of the complete Ni/$NiSi_2$/Si/Ni system.

3.2. Linear Behaviour of the Current–Voltage Characteristic

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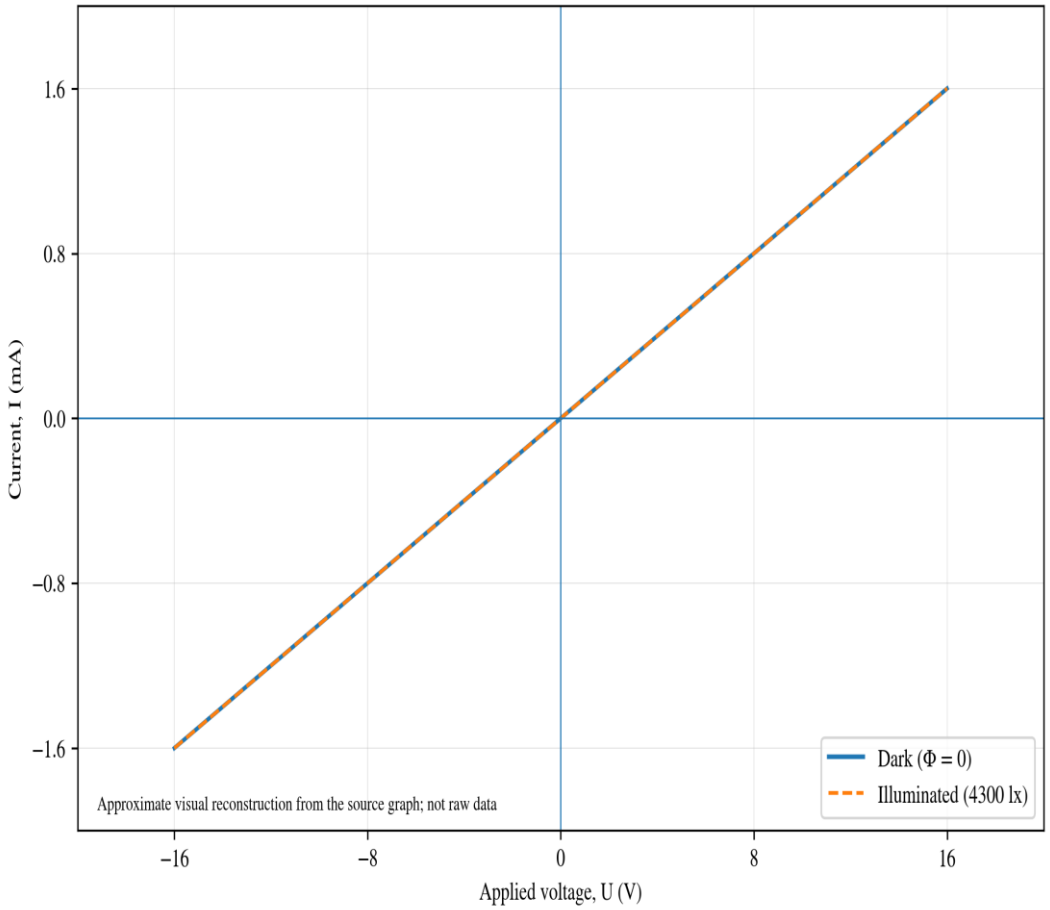


Figure 2. Approximate English-language reconstruction of the current–voltage characteristic shown in Figure 4.14 of the author's PhD dissertation [1]. The plotted line is a visual reconstruction from the source graph, not a set of original raw measurement points.

Figure 2 presents an English-language reconstruction of the source graph. The current is almost linearly dependent on the applied voltage. The forward- and reverse-bias branches meet close to the origin. The curves representing the dark condition (Φ = 0) and illumination at 4300 lx are reported in the source to be close to one another within the resolution of the original graph.

From the scale of the graph, a point of approximately U ≈ 16 V and I ≈ 1.6 mA can be estimated. The corresponding preliminary estimate of the effective resistance is:

$$R \approx \frac{16\ \text{V}}{1.6 \times 10^{-3}\ \text{A}} \approx 10^4\ \Omega = 10\ \text{k}\Omega \quad (4)$$

The corresponding conductance is approximately:

$$G \approx \frac{1}{10^4\ \Omega} = 100\ \mu\text{S} \quad (5)$$

The values of 10 kΩ and 100 μS are not exact results taken from the original measurement table; they are approximate values visually estimated from the graph in the

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dissertation. They should therefore be identified as graph-based estimates. The original U–I data points or the measurement record from the source-measure unit (SMU) are required to obtain accurate values.

The linear I–V characteristic indicates that the complete contact system exhibits effectively ohmic behaviour over the measured voltage range. This does not mean that the Schottky barrier at the interface is absent: the barrier parameter of an individual interface and the overall current–voltage response of a multilayer contact system describe different physical aspects.

3.3. Equivalent Electrical Model of the Contact System

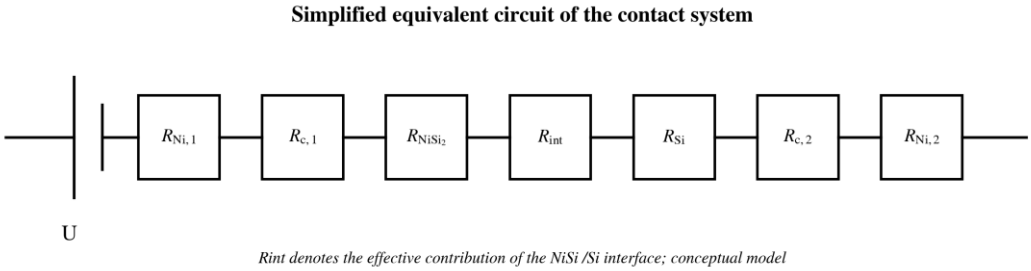


Figure 3. Simplified equivalent series-resistance model of the Ni/NiSi₂/Si(111)/Ni contact system. This is a conceptual model and does not imply that each individual resistance was measured independently.

The total resistance of the contact system can be represented, in a simplified form, as the sum of the contributions from the metal electrodes, the $NiSi_2$ ultrathin layer, the $NiSi_2$/Si interface, and the silicon substrate:

$$R_{\Sigma} = R_{\mathrm{Ni},1} + R_{\mathrm{c},1} + R_{\mathrm{NiSi_2}} + R_{\mathrm{int}} + R_{\mathrm{Si}} + R_{\mathrm{c},2} + R_{\mathrm{Ni},2} \quad (6)$$

This model is useful for interpreting the linear I–V characteristic. If, over the measured range, the current through the interface is proportional to the applied voltage, or if the interface resistance contributes to an effectively linear regime of the total resistance, the I(U) dependence of the complete system may appear linear. However, the available sources do not provide separate values for each resistance component in this equivalent circuit.

3.4. Relationship Between the Schottky Interface and the Linear I–V Characteristic

The source reports a Schottky barrier height of 0.63 eV for the $NiSi_2$/Si(111) interface [1, 2]. For an ideal rectifying Schottky contact, the thermionic-emission model can be written as:

$$I = I_s\left[\exp\left(\frac{qU}{nk_BT}\right) - 1\right] \quad (7)$$

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$$I_s = AA^* T^2 \exp\left(-\frac{q\Phi_B}{k_B T}\right) \quad 8)$$

Here, Is is the saturation current, q is the elementary charge, U is the applied contact voltage, n is the ideality factor, kB is the Boltzmann constant, T is the absolute temperature, A is the contact area, A* is the effective Richardson constant, and ΦB is the Schottky barrier height. These equations are included as a theoretical reference for an ideal rectifying contact. The parameters of this model have not been fitted to the available linear graph.

Therefore, the reported barrier height of 0.63 eV and the linear I–V characteristic of the complete system do not necessarily represent contradictory results. A definitive interpretation requires clarification of the actual substrate doping type and concentration, contact geometry, interface condition, and measurement configuration. Rectifying Schottky behaviour at epitaxial $NiSi_2$/n-Si(111) interfaces has also been reported in the literature [3, 4].

3.5. Effects of Illumination and Temperature

In the original graph, the curves for the dark condition and illumination at 4300 lx appear almost superimposed. The resolution of the available image does not allow small differences in current to be quantified. The sensitivity to illumination can be evaluated using the following parameter:

$$S_\Phi = \frac{\Delta I}{\Delta \Phi} \quad 9)$$

Here, ΔI is the difference between the currents measured under illuminated and dark conditions, and ΔΦ is the change in illumination. The sensitivity coefficient was not calculated because the original U–I data points are unavailable.

The dissertation and monograph report that the contact properties remain practically unchanged when the system is heated to approximately 700 K [1, 2]. The temperature coefficient of resistance can be expressed as:

$$\alpha_R = \frac{R(T) - R(T_0)}{R(T_0)(T - T_0)} \quad 10)$$

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At least two resistance values measured at different temperatures are required to determine this coefficient numerically. Since the available sources provide only a qualitative statement that the contact quality remains practically unchanged, no numerical value of αR is reported here.

4. Discussion

The analyzed results reveal three important features of the contact system incorporating a $NiSi_2$ ultrathin layer. First, the $NiSi_2$ layer has low resistivity and acts as a conducting layer. Second, the I–V characteristic of the complete Ni/$NiSi_2$/Si(111)/Ni system is nearly linear over the measured range. Third, the retention of the contact properties up to approximately 700 K indicates thermal stability of the system.

These results should be considered together with literature data on the electronic structure and crystallographic quality of the $NiSi_2$/Si interface. Tung et al. emphasized that surface cleaning and annealing conditions affect the barrier height at the $NiSi_2$/Si(111) interface [3]. Parui et al. reported local variations in the Schottky barrier in epitaxial $NiSi_2$/n-Si(111) systems and showed that an additional Ni layer may influence electron transmission through the interface [4].

An important aspect of the present analysis is that the electrical characteristic is not treated solely as a property of the $NiSi_2$ material. Instead, it is considered as the response of the complete system consisting of Ni electrodes, an ultrathin silicide layer, the interface, and the Si substrate. This approach more closely reflects the operating conditions of a practical contact structure.

5. Conclusions

1. Formation of a 30–40 Å (3–4 nm) $NiSi_2$ ultrathin layer on Si(111) by Ni^+ ion implantation followed by thermal annealing at approximately 900 K is reported in the source studies.

2. The current–voltage characteristic of the Ni/$NiSi_2$/Si(111)/Ni contact system is nearly linear under both forward and reverse bias. The total resistance estimated from the graph is approximately 10 kΩ; this value is a preliminary graph-based estimate.

3. The resistivity of the $NiSi_2$ layer is reported as 4×10^{-5} Ω·cm, while the Schottky barrier height at the $NiSi_2$/Si(111) interface is 0.63 eV. These parameters describe different physical properties of the layer and the interface.

4. The I–V curves recorded in the dark and under illumination at 4300 lx are close to one another within the resolution of the available graph. Original measurement points are required to calculate the photosensitivity coefficient accurately.

5. The reported retention of contact properties up to approximately 700 K indicates the potential of $NiSi_2$ ultrathin films as thermally stable contact materials.

6. Further work should include new measurements of the I–V characteristics at different temperatures, determination of the specific contact resistance with the contact geometry taken into account, and a

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separate analysis of the charge-transport mechanism at the interface.

6. Issues Requiring Clarification in the Source Data

1) The substrate type is inconsistent within the source: the caption of the I–V figure identifies n-Si, whereas the electrical-parameter table specifies p-type Si(111) with Np = 10^{17} cm^{-3}. For this reason, the substrate is referred to neutrally as Si(111) throughout this draft. The actual doping type must be verified before journal submission.

2) The PhD dissertation and monograph report a $NiSi_2$ resistivity of 4×10^{-5} Ω·cm (40 μΩ·cm) in one section, whereas another section gives 60–80 μΩ·cm. These values may correspond to different samples or measurement conditions. They should not be combined into a single value without checking the original laboratory records.

3) The estimated resistance of approximately 10 kΩ was obtained from the scale of the I–V graph. The original U–I data table or measurement file is required before this value can be presented as an exact experimental result.

4) Thermal stability up to 700 K is reported qualitatively in the source. Since no R(T) dataset is provided, the temperature coefficient, activation energy, and percentage thermal drift have not been calculated.

5) This paper is an analytical re-examination of results previously reported in the author's PhD dissertation and monograph. It should not be presented as a new laboratory measurement. Before claiming a new DSc result, an independent contribution should be established through new experiments, reprocessed original data, or a separately validated theoretical model.

REFERENCES:

[1] Tung, R. T., Ng, K. K., Gibson, J. M., & Levi, A. F. J. (1986). Schottky-barrier heights of single-crystal $NiSi_2$ on Si(111): The effect of a surface p-n junction. Physical Review B, 33(10), 7077–7090. https://doi.org/10.1103/PhysRevB.33.7077.

[2] Parui, S., Wit, B., Bignardi, L., Rudolf, P., Kooi, B., van Wees, B. J., & Banerjee, T. (2011). Hot electron transmission in metals using epitaxial $NiSi_2$/n-Si(111) interfaces. Applied Physics Letters, 99, 032104. https://doi.org/10.1063/1.3610458.

[3] Umirzakov, B. E., Tashmukhamedova, D. A., Tashatov, A. K., & Mustafoeva, N. M. (2019). Electronic and optical properties of $NiSi_2$/Si nanofilms. Technical Physics, 64(5), 708–710. https://doi.org/10.1134/S1063784219050244. Russian-language version: Journal of Technical Physics, 89(5), 759–761 (2019), https://doi.org/10.21883/JTF.2019.05.47481.192-18. [The two journal records refer to the same article and are listed once.]

[4] Tashatov, A. K., & Mustafoyeva, N. M. (2020). Surface morphology of $NiSi_2$/Si films obtained by the method of solid-phase deposition. Journal of Surface Investigation: X-

Latin American Journal of Education
www.lajoe.org

ray, Synchrotron and Neutron Techniques, 14(1), 81–84. https://doi.org/10.1134/S1027451020010188.

[5] Umirzakov, B. E., Tashmukhamedova, D. A., Tashatov, A. K., Mustafoeva, N. M., & Muradkabilov, D. M. (2020). Effect of the disordering of thin surface layers on the electronic and optical properties of Si(111). Semiconductors, 54(11), 1424–1429. https://doi.org/10.1134/S1063782620110263.

[6] Mustafaeva, N. M., Tashatov, A. K., Mustafaeva, N. M., & Mavlonova, X. J. (2022). Investigation of physical properties of $NiSi_2$/Si nanofilm. Pioneer: Journal of Advanced Research and Scientific Progress (JARSP), 1(4), 9–11. ISSN 2751-7551.

[7] Mustafoeva, N. M., Tashatov, A. K., Mustafaeva, N. M., & Mavlonova, X. J. (2022). Surface morphology of $NiSi_2$/Si films produced by solid-phase epitaxy. Pioneer: Journal of Advanced Research and Scientific Progress (JARSP), 1(4), 5–8. ISSN 2751-7551.

[8] Mustafoeva, N. M., Tashatov, A. K., & Umirzakov, B. E. (2023). On the band-gap width of $NiSi_2$ nanocrystals created in the surface region of Si using ion implantation. Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques, 17(2), 415–418. https://doi.org/10.1134/S1027451023020106.

[9] Tashatov, A. K., Mustafoeva, N. M., Jumanov, Sh., & Mustafaeva, N. (2024). Obtaining a multilayer nanosystem Si/$NiSi_2$/Si by solid-phase deposition method. QarDU xabarlari, 2024(1), 11–14.

[10] Umirzakov, B. E., Donaev, S. B., & Mustafaeva, N. M. (2019). Electronic and optical properties of GaAlAs/GaAs thin films. Technical Physics, 64(10), 1506–1508. https://doi.org/10.1134/S1063784219100220.

[11] Toshmuhamedova, D. A., Umirzakov, B. E., & Tashatov, A. K. (2000). Properties of SiO_2 dielectric films. Uzbek Physics Journal, 2, 38. [Bibliographic details reproduced from the information supplied by the author; issue and full page range were not independently verified.]