AIP | Applied Physics Letters

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Citation: Applied Physics Letters **55**, 84 (1989); doi: 10.1063/1.102392
View online: http://dx.doi.org/10.1063/1.102392
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/55/1?ver=pdfcov
Published by the AIP Publishing

Electronic transport properties of epitaxial erbium silicide/silicon heterostructures

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(Received 9 February 1989; accepted for publication 21 April 1989)

We studied electrical parallel and perpendicular transport in thin epitaxial erbium silicide films obtained by solid phase reaction and by codeposition of Er and Si on (111) Si. Resistivity measurements show that the silicide is metallic with a room-temperature resistivity of 34 $\mu\Omega$ cm; the dependence of the Hall coefficient on temperature can be explained by a two-band conduction model. Magnetic effects are shown to affect the low-temperature resistivity and the Hall coefficient. Perpendicular transport properties are studied by electrical [current-voltage $I(V)$ and capacitance-voltage $C(V)$ characteristics] and internal photoemission methods on erbium silicide/n- or p-type Si diodes. The p-type diodes have a perfect rectifying behavior with a Schottky barrier height of about 0.74 eV measured by $I(V)$ and photoemission methods. The n-type junction is ohmic at room temperature and rectifying at low temperatures; $C(V)$ and optical measurements yield a Schottky barrier height of about 0.28 eV. Some potential applications of erbium silicide/Si heterostructures are presented.

Silicide/silicon heterostructures are of considerable interest for their numerous applications in microelectronics.[1] Most of the work published so far concerns transition metal silicides; they are also used in the fabrication of the metal base transistors.[2] The rare-earth silicides are of particular interest because of their low Schottky barrier heights on n-type silicon[3] and the magnetic properties due to the rare earths. Some magnetic and structural properties of the silicides deposited on Si[3–6] have been examined. Their electrical properties are not fully known and published results[3,7] show that several questions remain open. Thanks to an improved technique of crystal growth, we recently obtained thin erbium silicide (ERS) films epitaxially grown on (111)Si. In this letter we present the first extensive study of both parallel and perpendicular transport properties of ERS/Si heterostructures.

The silicide films were grown on (111)Si 10^4 Ω cm by ultrahigh vacuum (10^{-10} Torr) codeposition of Er and Si in the atomic ratio 1:2, followed by a solid-state reaction at 400 °C, and subsequently annealed at more elevated temperatures. Electron and x-ray diffraction, low-energy electron diffraction, Rutherford backscattering (RBS), and transmission electron microscopy were used for evaluating the layer quality: the ERS films are epitaxial and monocrystalline. Details on preparation methods, film morphology, and characterization methods are presented elsewhere.[8]

We studied first parallel transport in thin ERS films. The thickness determined by RBS measurements was found to be 330 Å. Experimental details of the resistivity ρ and the Hall coefficient R_H measurements have been previously described.[9] The contacts on the silicide films exhibited an ohmic behavior. The resistivity at 300 K was found to be 34 $\mu\Omega$ cm; its variation with temperature down to 2 K is shown in Fig. 1. The resistivity decreases linearly with decreasing temperature and tends toward a limiting value of about 10 $\mu\Omega$ cm. However, at 4.5 K, $\rho(T)$ rapidly changes slope and decreases to reach 8.5 $\mu\Omega$ cm at 2 K. The linear decrease of $\rho(T)$ is typical of a metal and is related to phonon scattering (Mathiessen's law); it should be noted that the phonon contribution $\Delta\rho_{\text{phonon}}$ (24 $\mu\Omega$ cm) is slightly higher than that of $CoSi_2$ (15 $\mu\Omega$ cm) and is smaller than that of other rare-earth silicides (≈ 100 $\mu\Omega$ cm).[4] The abrupt decrease of $\rho(T)$ below 4.5 K is attributed to magnetic ordering, which has previously been observed in magnetic susceptibility.[4] This effect follows from suppression of electron scattering by randomly oriented atomic spins, induced by magnetic ordering. The residual resistivity, at 0 K, due to crystallographic defects is less than 9 $\mu\Omega$ cm indicating a relatively good crystallinity. It seems therefore unlikely that ERS films can be obtained with a resistivity lower than 25 $\mu\Omega$ cm at 300 K which should be compared with the 15 $\mu\Omega$ cm resistivity of $CoSi_2$.

The variation of R_H with temperature is shown in Fig. 2. The Hall coefficient is positive at 300 K, then decreases and becomes negative below 150 K. Subsequently, below 20 K R_H increases slightly and exhibits a cusp at 4.5 K. The sign of R_H indicates that the majority carriers are holes above 150 K and electrons below 150 K. The contribution of both elec-

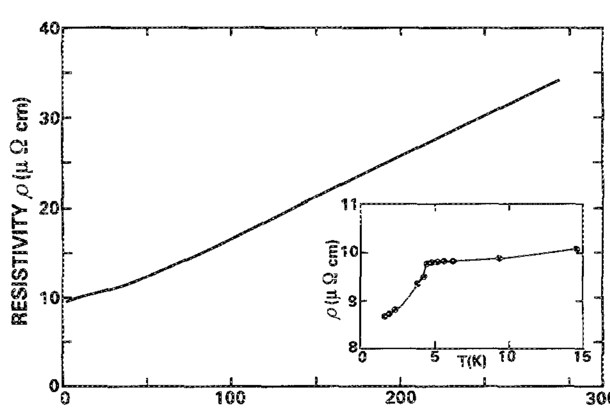

FIG. 1. Resistivity of a 300-Å-thick erbium silicide film, as a function of temperature. The main curve shows the linear decrease of the resistivity with decreasing temperature, typical of a metal and due to phonon scattering. The inset shows the details of the curve at low temperatures and the occurrence of a magnetic transition at 4.5 K.

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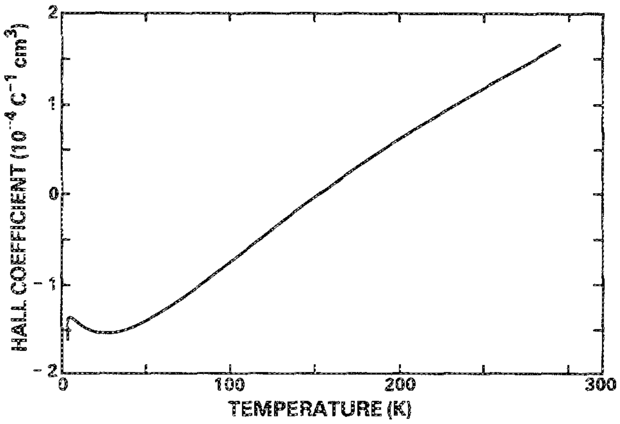

FIG. 2. Hall coefficient R_H of a 300-Å-thick erbium silicide film as a function of temperature T. The sign of R_H indicates that the majority carriers, above 150 K, are holes and are electrons, below 150 K. The evolution of R_H with temperature can be explained by a two-band conduction model, with hole and electron mobility varying with T.

trons and holes to the conduction has also been observed in several nonmagnetic silicides WSi_2,[10,11] $MoSi_2$,[12] and $TiSi_2$.[13] This behavior is typical of semimetals.[10] Thus, R_H depends on density and mobility of both electrons and holes. If their concentrations are comparable, the changes of hole and electron mobilities with temperature lead to positive or negative values of R_H. We cannot, at this point, calculate the carrier density and can only give an upper bound value of 3×10^{22} cm^{-3} for both densities. Magnetic properties are involved in the low-temperature part of the R_H curve and are responsible for the cusp at 4.5 K. Indeed, the abrupt increase of the carrier mobility with magnetic ordering leads to a drastic change of R_H.

Second, we studied perpendicular transport using ERS/Si diodes prepared with a 300-Å-thick ERS film grown on (111)Si. We used n- and p-type degenerate substrate wafers with an epitaxial 3×10^{15} cm^{-3} buffer layer on top. The diodes were fabricated by standard lithographic and chemical etching techniques, with diameters varied from 0.25 to 1.50 mm. We observed an excellent rectifying behavior of the ERS/p-type Si diodes, shown in Fig. 3. The diode leakage current at RT was lower than 10^{-8} A at 1 V, while the saturation current approached 10^{-2} A for a diameter of 0.25 mm. The ideality factor, measured for the current spanning five orders of magnitude of the forward current, was found to be 1.03 , the value indicating a high perfection of the diode. From the extrapolated value of the forward current at zero bias, and using a Richardson constant[14] of 80 A cm^{-2} K^{-2}, we calculated a Schottky barrier height of ERS on p-type Si, $\varphi_p = 0.73 \pm 0.01$ eV at 300 K. This result was confirmed by internal photoemission measurements. The diode was illuminated by a monochromatic chopped light (double prism monochromator) and the signal was measured by a phase sensitive detector. The photon flux was measured by means of a beamsplitter and the photocurrent was normalized by the number of photons. Figure 4 shows the usual Fowler plot, i.e., the square root of the photocurrent versus photon energy. The curve concerning the ERS/p-type diode was linear from 0.85 to 1 eV and leads to a barrier height $\varphi_p = 0.740 \pm 0.002$ eV at RT. The 2 meV uncertainty corresponds to the accuracy of the fit while the observed dispersion from one diode to another was about 5 meV. The φ_p value is consistent with that previously published[3,7] and comparable with that of other rare-earth silicides.[3,7] Its high value explains the perfect rectifying behavior and the low leakage current of the diodes.

We performed the same $I(V)$, $C(V)$, and optical experiments on ERS/n-type Si junctions. They were ohmic at RT and rectifying at 77 K with forward and reverse currents of the order of 2×10^{-2} and 2×10^{-5} A, respectively, for a diode of 1 mm diameter under 1 V bias. We could not, however, calculate accurately the barrier height from the $I(V)$ curve because of its degraded ideality. The barrier height determinations by $C(V)$ measurements were possible at 77 K and gave $\varphi_n = 0.29 \pm 0.01$ eV. Internal photoemission measurements were also performed on these diodes at 77 K. As shown in Fig. 4, the Fowler plot appeared to be linear from 0.5 to 0.8 eV and the deduced barrier height φ_n was found to be 0.280 ± 0.004 eV. The determination of φ_n by linear extrapolation of the Fowler plot was somewhat less accurate than for φ_p because the experimental values near the threshold were not available; indeed the photon flux de-

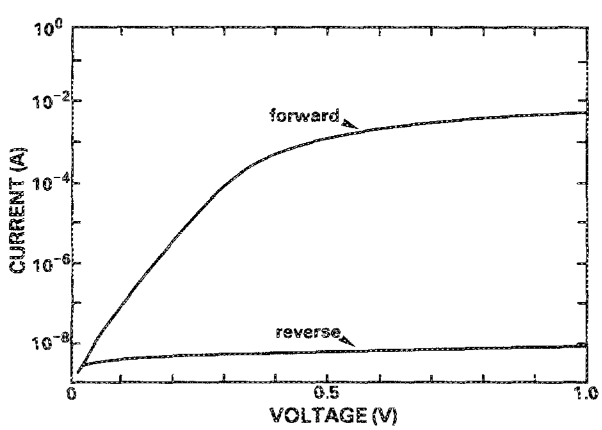

FIG. 3. $I(V)$ curve of an erbium silicide/p-type Si diode of 0.25 mm diameter. Vertical axis is on logarithmic scale. The upper (lower) part of the curve represents the forward (reverse) current. The ideality factor is 1.03 and the extrapolated Schottky barrier height is 0.73 eV.

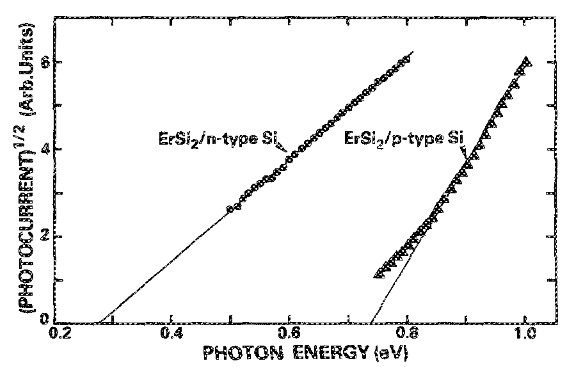

FIG. 4. Square root of the photocurrent in erbium silicide/Si diodes per incident photon as a function of photon energy. The Fowler plot on the right (left) is for the diodes on p-type, at 300 K (n-type, at 77 K) Si. The linear extrapolation of the curves to zero current yields a Schottky barrier height for erbium silicide of 0.74 eV on p-type Si and 0.28 eV on n-type Si.

creased drastically below 0.5 eV due to a strong light absorption in the optical apparatus. Nevertheless, the accuracy of optical barrier height determination (2 meV for φ_p and 4 meV for φ_n) was always better than that of electrical determinations (10 meV). It should be emphasized that the values of φ_n optically and electrically obtained are self-consistent and are clearly smaller than that previously published.[3] The latter has been obtained by fitting linearly a log $I(V)$ curve with a current showing no evident exponential dependence. The low barrier height φ_n explains the ohmic behavior of the ERS/n-type Si diode at RT. Finally, it should be noted that the sum $\varphi_n + \varphi_p$ is equal to 1.020 ± 0.006 eV, the value by about 100 meV smaller than the silicon band gap $E_G = 1.115$ eV. The given values φ_n and φ_p were not corrected for the image force lowering (Schottky effect) which is about 15 meV at zero applied bias; therefore, the silicon band gap has to be compared with the value $\varphi_n + \varphi_p + 0.030 \pm 0.006$ eV $= 1.050$ eV, the latter being still smaller than E_G. This slight discrepancy is not yet explained.

In conclusion, this study of parallel transport properties of erbium silicide thin films demonstrated its metallic properties explainable in terms of a two-band conduction model. The coupling of magnetic and electronic transport properties in the rare-earth silicides permits studying various aspects of spin interactions, which is a subject of prime importance for basic research. The unexpectedly low resistivity, comparable with that of transition metal silicides like $CoSi_2$, confirmed the good crystallinity of the MBE-grown silicide and is promising for microelectronic applications. We measured the Schottky barrier height of ERS on both p- and n-type Si using $I(V)$, $C(V)$, and internal photoemission methods. The high barrier height on p-type (0.740 eV) combined with the extremely low barrier height on n-type Si (0.280 eV) makes ERS an ideal candidate for applications requiring low access resistance, such as contacts in microwave bipolar transistors. An improved accuracy of the Schottky barrier height determination should be emphasized as important for further work in this field. Finally, a low lattice mismatch between Si and ERS allows the regrowth of Si on top of ERS and should permit a realization of superlattices, interesting applications of which could be a p-type metal base transistor and a near-infrared detector.

We are indebted to Christine Puissant and Yves Campidelli for their excellent work on sample preparation.

[1] S. Saitho, H. Ishiwara, T. Asano, and S. Furukawa, Jpn. J. Appl. Phys. **20**, 1649 (1981).
[2] E. Rosencher, F. Arnaud d'Avitaya, P. A. Badoz, C. d'Anterroches, G. Glastre, G. Vincent, and J. C. Pfister, Mater. Res. Soc. Symp. Proc. **91**, 415 (1987).
[3] K. N. Tu, R. D. Thompson, and B. Y. Tsaur, Appl. Phys. Lett. **38**, 626 (1981).
[4] J. Pierre, E. Siaud, and D. Frachon, J. Less Comm. Metals **139**, 321 (1988).
[5] J. A. Knapp and S. T. Picreaux, Appl. Phys. Lett. **48**, 466 (1986).
[6] J. A. Knapp and S. T. Picreaux, Mater. Res. Soc. Symp. **54**, 261 (1986).
[7] H. Nordes, J. De Sousa Pires, F. d'Heurle, F. Pesavento, S. Petersson, and P. A. Tove, Appl. Phys. Lett. **38**, 865 (1981).
[8] F. Arnaud d'Avitaya, A. Perio, J.-C. Oberlin, Y. Campidelli, and J. A. Chroboczek, Appl. Phys. Lett. **54**, 2198 (1989).
[9] J. Y. Duboz, P. A. Badoz, E. Rosencher, J. Henz, M. Ospelt, H. von Känel, and A. Briggs, Appl. Phys. Lett. **53**, 788 (1988).
[10] P. A. Badoz, E. Rosencher, J. Torres, and G. Fishman, J. Appl. Phys. **62**, 890 (1987).
[11] T. L. Martin, V. Malhotra, and J. E. Mahan, J. Electron. Mater. **13**, 309 (1984).
[12] T. L. Martin and J. E. Mahan, J. Mater. Res. **1**, 493 (1986).
[13] V. Malhotra, T. L. Martin, and J. E. Mahan, J. Vac. Sci. Technol. B **2**, 10 (1984).
[14] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), Chap. 5.