Transistor action in Si/CoSi$_2$/Si heterostructures

J. C. Hensel, A. F. J. Levi, R. T. Tung, and J. M. Gibson

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

We report transistor action in a Si/CoSi$_2$/Si structure. The thin silicide layer (< 100 Å), which acts as the base, is a single-crystal metal, essentially continuous and locally exhibiting atomically perfect interfaces with Si. The transistor action is manifested by a common base current gain α as high as 0.6 and a voltage gain greater than 10.

Thin, metallic films of transition metal silicides have achieved considerable technological importance in microcircuits mostly in a passive sense as contacts and interconnects.[1] In these applications, crystallinity and interface perfection *per se* are not of overriding importance. Recent developments,[2] however, in the art of growing single-crystal silicide films now permit one to contemplate the next level of sophistication wherein the metal film would assume a more active role as a device element. Devices of this kind, e.g., the metal base transistor[3] and permeable base transistor,[4] were envisioned many years ago, but efforts toward their realization have been hampered largely by materials-related problems. Possibilities are now at hand for an advanced class of integrated metal/silicon devices. In this letter we report the fabrication of a single-crystal, vertically integrated Si/CoSi$_2$/Si heterostructure and demonstrate, for the first time, transistor action in this type of structure.

The trilayer structure in these experiments consisted of CoSi$_2$ epitaxially grown on a Si substrate with a subsequent overgrowth of Si (see Fig. 1).[5] Each layer is a single crystal. CoSi$_2$ was used because it has a long carrier scattering length[6,7] (≈ 200 Å) at room temperature. The Si overlayer was n doped to a concentration of $N_d \approx 10^{15}$–10^{16} Sb/cm^3 by codeposition of Sb from an effusion cell together with Si. In some cases the surface 300 Å layer of Si was degenerately doped to ensure an ohmic contact. The substrate doping was typically 10^{17} cm^{-3}. The CoSi$_2$ layer was typically 100 Å thick and was seen to be of excellent quality, as evidenced by transmission electron microscopy (TEM), i.e., single crystal, essentially continuous, and locally having atomically perfect interfaces with substrate and overgrown Si. These structures have been characterized by Rutherford backscattering (RBS), which shows the Si overlayer to be single crystal (a channeling-to-random RBS yield ratio $\chi_{min} \approx 4\%$) with planar interfaces. TEM also showed that there exists a low density (fractional area of several percent) of openings in the silicide containing columns of silicon of radii of the order of a few times the silicide film thickness.

The trilayer structures were processed in a sequence of steps involving photolithographic masking and plasma (CF$_4$) etching to produce an array of mesas (~ 50 or more per sample) of the kind shown in Fig. 2. Following convention we designate the top Si layer the emitter, the CoSi$_2$ layer the base, and the Si substrate the collector. Electrical contacts were made to the emitter (n^+ surface) by metallization with Ti-Au and to the collector with silver paste applied to a large area n^+ contact prepared by Sb evaporation followed by laser alloying. Contact was made to the exposed CoSi$_2$ with a rounded tungsten probe.

Electrical characteristics (common base) of one device are shown in Fig. 3(a). The traces represent collector current I_c vs collector voltage V_c, each trace corresponding to a different level of emitter current injection I_{ee}. The lowest trace, $I_{ee} = 0$, is typical of the I-V behavior for a Schottky barrier (collector/base). At finite levels of injection the curves are qualitatively the same but displaced upwards on the current scale, this displacement representing some fraction αI_{ee} of the injected current reaching the collector. That there exists a substantial current injection across the base to the collector is evident, and that this is not simply ohmic conduction is seen from the form of the characteristics. For this device $\alpha \sim 0.5$ as measured at $V_c = 0$. In other devices α's as high as 0.6 have been observed. There is a marked similarity of the curves in Fig. 3(a) to the common base characteristics of a bipolar transistor; one feature of note, characteristic of injection devices, is the nonzero value[8] of I_c at $V_c = 0$ for finite I_{ee}.

Common emitter characteristics (I_c vs V_c for various levels of current injection I_{ee} in the base) are shown in Fig. 3(b). Again there is a marked similarity to the characteristics of a (low α) bipolar transistor. The main point here is that in the context of a simple model (see below) $\Delta I_c \approx \beta \Delta I_{ee}$ for positive V_c, so for the lowest curves in Fig. 3(b) $\beta \approx 1.2$ which is consistent with the above-mentioned α value according to the usual relationship $\beta = \alpha/(1 - \alpha)$.

Electron transport in the device can follow two paths (see Fig. 4): (1) transport of electrons through connecting columns of Si in the metal base (semiconductor transport, ST) and (2) injection of electrons over a Schottky barrier (barrier height $\phi_b = 0.64$ eV)[9] into the metal base (metal injection, MI) with the intriguing possibility that some of the injected electrons may transport ballistically across the base as envisaged in the metal base transistor.[3] In the ST case, electrons pass through holes in the metal base directly from emitter to collector; however, this does not constitute a "short," for there is a potential barrier in the hole which may be comparable to ϕ_b if the depletion width is appreciably greater than the hole radius r_0. In fact, one can model this by making the reasonable assumption that the potential is pinned to ϕ_b at the edges of the hole and dips parabolically to some minimum $\phi_b - \Delta_0$ at the center of the hole, forming an overall potential surface in the shape of a saddle. This differs from the operating regime of a conventional permeable base transistor in that Δ_0 is small and there is appreciable MI. The barrier lowering Δ_0 is some function of r_0, the impurity concentration, and the emitter and collector biases. Inasmuch as the barrier height is tied to the base, a forward bias on the emitter will inject electrons over the reduced potential
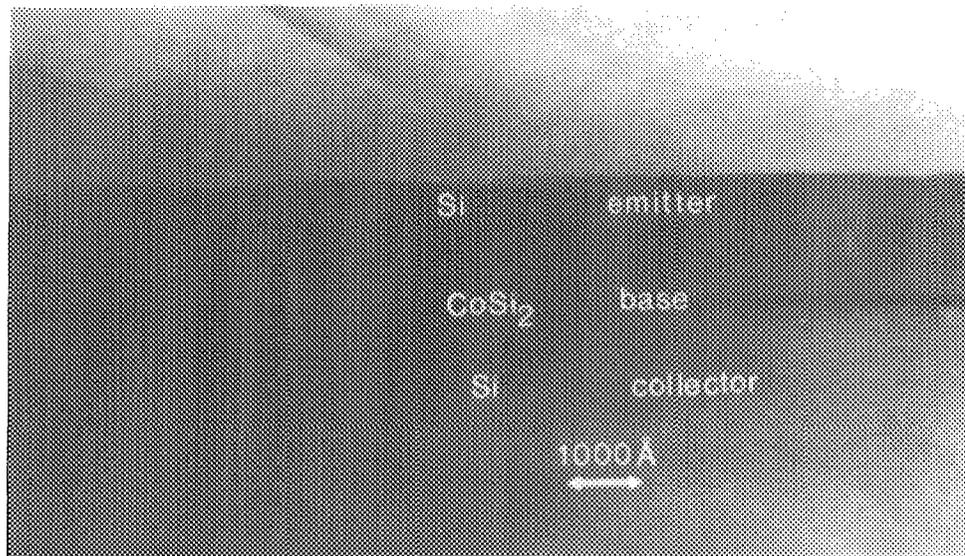
FIG. 1. Cross-section TEM image of a trilayer Si/CoSi$_2$/Si structure similar to the device described in the text. The upper light-grey region is epoxy resin used in specimen preparation.

$\phi_b - \Delta_0$, the fastest base transit time being $\tau \sim d / v_s \lesssim 10^{-13}$s, where $v_s = 10^7$ cm/s is the saturation velocity in Si.

We have constructed a phenomenological model for such a device which incorporates both MI and ST channels. The two operate in parallel but *not* independently. For MI we assume charge transport across the emitter Schottky barrier to be governed by the usual thermionic emission theory. For ST charge transport occurs by activation over the reduced barrier in the hole which we have modeled by solving Poisson's equation for the appropriate geometry. The I-V characteristics that are generated by the model are not unlike those of an ordinary bipolar transistor and qualitatively agree with the observed traces shown in Fig. 3.

The measured α implies that both the ST and MI currents are comparable in magnitude. Inasmuch as openings do exist in the base, it is likely that they carry a substantial fraction of the current; however, we cannot rule out the possibility that some fraction of MI current is transported ballistically across the base. This ambiguity is due to the fact that in both types of transport, current flows by thermal activation over a controlled potential barrier and, broadly speaking, the characteristics of any such charge-controlled device (including the bipolar transistor) are fundamentally the same.
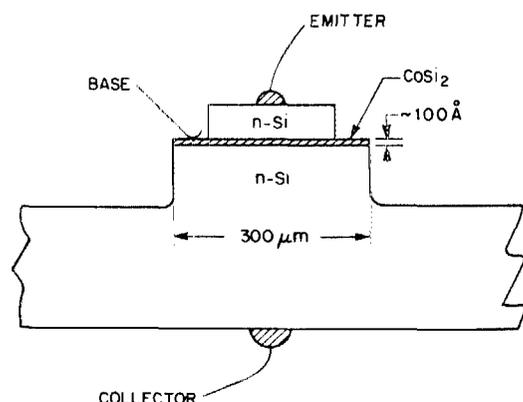
Theoretically, stringent conditions must be satisfied for appreciable coherent ballistic transmission in the metal: (1) The interfaces must be smooth, parallel, and commensurate so the wave vector parallel to the interface $k_\parallel$ will be conserved; (2) metal Bloch states with the same $k_\parallel$ and energy E as the incident (and hence the coherently transmitted) Si states must exist; (3) the metal scattering length l must be large compared to the base thickness d. In addition, for good performance, the transmission at each interface must be high which requires similarity between the Si and metal wave functions and a smooth interface potential. For a rough interface and/or $l \ll d$, either of which could break the kinematical matching conditions, the chance of an incident electron's "hitting" an allowed state in the Si collector is greatly reduced. We wish to point out that requirements (1) and (3) are met in the structures studied by us. The second requirement is problematical.
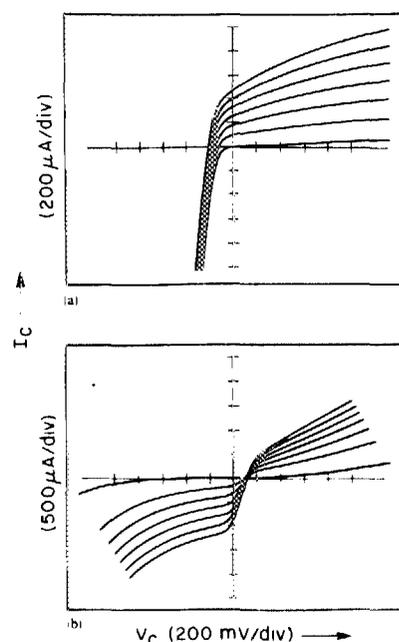

FIG. 3. Device I-V characteristics: (a) common base configuration; (b) common emitter configuration. Curves were taken in steps of 200 μA beginning with $I_{ee} = 0$.

FIG. 2. Schematic cross section of a single mesa device fabricated from an epitaxial Si/CoSi$_2$/Si heterostructure.
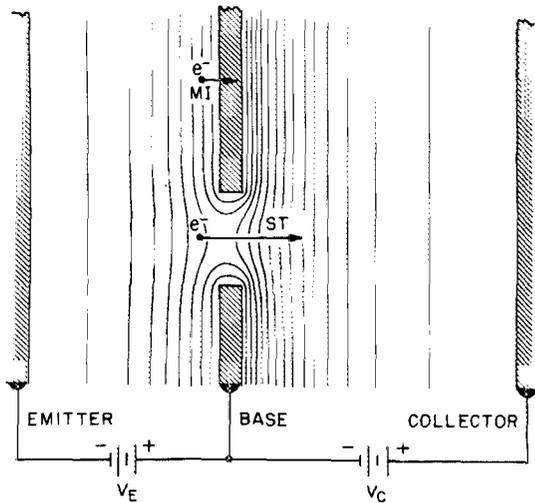
FIG. 4. Model for electron transport in a Si/CoSi$_2$/Si heterostructure device: transport of electrons through small apertures in the metal base (ST) as schematically illustrated by equipotential contours showing a "saddle" in the potential; and injection into the metal base (MI).

As a final demonstration of transistor action we have observed a voltage gain greater than 10 in a test circuit employing a common base configuration with a load resistor of $R_L = 5000\,\Omega$ and an emitter current of $I_E \approx 1$ mA. Amplification has been observed at frequencies up to 1 MHz, limited mainly by the test circuit used. The gain falls short of ideal, $A = g_m R_L \sim 100$, which we attribute to deficiencies in contacts. [Here, g_m is the device transconductance given by $g_m = \alpha(e/k_B T)I_E$.]

In conclusion, we have for the first time demonstrated transistor action in a metal/semiconductor epitaxial structure. The transistor action is evidenced by both the dc elec-

trical characteristics of the device and the observation of appreciable ac voltage gain when the device is operated in a circuit. A new dimension in electronics technology is introduced with the possibility of novel high-speed devices being developed based on epitaxial overgrowth of silicon on ultrathin silicide layers. Furthermore, unique opportunities exist to study the physics of ballistic, hot-electron transport in a metal and electron transmission across a virtually ideal semiconductor/metal interface and through heterostructures and superlattices comprised of these interfaces.

[1]S. P. Murarka, *Silicides for VLSI Applications* (Academic, New York, 1983).

[2]R. T. Tung, J. M. Gibson, and J. M. Poate, Phys. Rev. Lett. **50**, 429 (1983).

[3]M. M. Atalla and D. Kahng, IRE Trans. Electron Devices **9**, 507 (1962); D. V. Geppert, Proc. IRE **50**, 1527 (1962); C. R. Crowell and S. M. Sze, Phys. Rev. Lett. **15**, 659 (1965).

[4]C. O. Bozler, G. D. Alley, R. A. Murphy, D. C. Flanders, and W. T. Lindley, IEEE Tech. Dig. Int. Electron Device Meet. 384 (1979).

[5]J. C. Bean and J. M. Poate, Appl. Phys. Lett. **37**, 643 (1980); S. Saitoh, H. Ishiwara, and S. Furukawa, Appl. Phys. Lett. **37**, 203 (1980).

[6]J. C. Hensel, R. T. Tung, J. M. Poate, and F. C. Unterwald, Appl. Phys. Lett. **44**, 913 (1984).

[7]J. C. Hensel, R. T. Tung, J. M. Poate, and F. C. Unterwald, in *Proceedings of the 17th International Conference on the Physics of Semiconductors, San Francisco*, 1984, edited by J. D. Chadi and W. A. Harrison (Springer, New York, 1985), p. 197.

[8]This feature, also reproduced in our modeled characteristics, represents a significant difference from the characteristics reported recently for a low α device ($\alpha \sim 0.02$) by E. Rosencher, S. Delage, Y. Campidelli, and F. Arnaud D'Avitaya, Electron. Lett. **20**, 762 (1984).

[9]R. T. Tung, J. Vac. Sci. Technol. B **2**, 465 (1984).