Nonlinear Unipolar Charge Transport in Silicon Microcontacts

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(Received 22 February 1989)

Contacts between heavily doped and moderately doped n-type silicon deviate drastically from conventional junctions upon shrinkage in size. Their resistance increases with increasing current injection, indicating a dipole of electron pileup and depletion near the resistivity discontinuity. Such microjunctions thus represent not the previously assumed ideal contacts but rather a novel type of Schottky barrier.

PACS numbers: 73.40.Lq, 72.80.Cw, 85.30.Hi

Electronic transport in solids can undergo dramatic changes upon reduction of the sample size, leading to nonlinear current versus voltage relations or to quantum phenomena.[1,2] In very small junctions of semiconductors, for example, we observed the onset of ballistic transport[3] and found a quenching of the phonon drag on the electrons[4] when the junction dimensions were limited so as to approach phonon mean free paths.

In this Letter, we report unusual phenomena of unipolar charge transport (i.e., only electrons and no holes) in n-type silicon microjunctions, where current flow is constricted by contacts in the μm range. Such size reduction causes nonlinear resistance; the current transport is diametrically opposite to the conventional concept of junctions between highly doped and lowly doped semiconductors of the identical conductivity type. Such junctions, usually termed "high/low junctions," were previously presumed to represent an "ideal contact" with a strictly linear relation between current and voltage. We show this assumption to be correct only for macroscopic dimensions. In microcontacts, the resistance *increases* with increasing current of electrons injected from the more heavily doped side, which is opposite to the conventional description. This nonlinearity is enhanced by contact size reduction. Highly localized variations of currents and fields are realized, as theoretically treated by Landauer.[5,6] These microcontacts are therefore not ideal Ohmic structures at all; rather they represent a novel type of Schottky barrier.

Silicon microcontacts are generated by adjoining two wedge-shaped samples in ultrahigh vacuum by means of a now highly developed technique, described in detail elsewhere.[3,4,7] The samples are cleaned by ion bombardment, inspected by Auger spectroscopy, and then pressed against each other in the final stage by a finely tuned piezoelectric drive. This method enables us to generate contacts of continuously variable areas as small as 10^{-10} cm^2. Currents, voltages, temperatures, and thermoelectric power can be monitored; the electrical and thermal resistances in the immediate vicinity of the microcontact constriction dominate all other resistive contributions by far.[7] All measurements reported here are performed at room temperature.

Here we describe experiments on so-called high/low junctions[8] of very heavily doped against moderately doped n-type silicon, conventionally termed n^+/n junctions. We deliberately utilize high doping; typically, $[n^+]=10^{19}$ electrons/cm^3, and $[n]=10^{16}$ electrons/cm^3. We are hence safely in a well-defined unipolar conduction regime; only electrons contribute to the current. Minority holes are negligible, since their densities $p=n_i^2/n$ are only of the order of 10^5 cm^{-3}, even for the less heavily doped wedge, since the intrinsic density is $n_i\approx10^{10}$ cm^{-3} for Si near room temperature. The silicon is of high perfection, and hence traps and recombination and generation centers are absent as appreciable sources for localized charges and minority carriers. Large-area junctions of such highly conductive silicon would present a very small resistance, any nonlinearity would be immeasurable, and the system would indeed appear to be an "ideal contact,"[8] for which high/low junctions often serve as model configurations.

Results for one n^+/n junction—out of a series of various combinations—are shown in Fig. 1. Plotted is the resistance $R=V/I$ to clearly reveal any deviation from an Ohmic relation between voltage V and current I. The junction with the largest area, curve g of Fig. 1, closely resembles the anticipated case for bulk conditions by showing an almost voltage-independent resistance, which is dominated by the Maxwellian spreading resistance[7,8]

$$R_M=\rho/L\,, \tag{1}$$

where ρ is the resistivity of the less heavily doped n wedge, and L is the diameter of the point contact. For ballistic electrons a "Knudsen resistance" must be considered,[7] which is, however, not necessary for the experimental conditions selected here.

Reduction of the contact diameter L leads to increasing asymmetry and nonlinearity in a fashion opposite to expectations according to the conventional description of high/low junctions.[9] The voltage polarity for the "forward direction," meaning low resistance, is conventionally the negative polarity to the heavily doped n^+ part, because this bias usually reduces the junction's potential $\phi_b=(kT/q)\ln([n^+]/[n])$, where q is the electron charge, k is Boltzmann's constant, T indicates tempera-

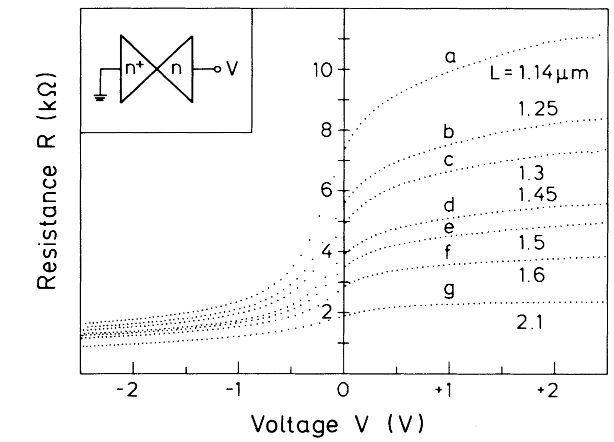

FIG. 1. Resistance R as a function of applied voltage V for an n^+/n microcontact with $[n^+]=10^{19}$ and $[n]=3\times10^{16}$ electrons/cm^3 by arsenic doping. Polarity definition is given in the inset. Parameter L is a nominal contact diameter, as derived by Eq. (1).

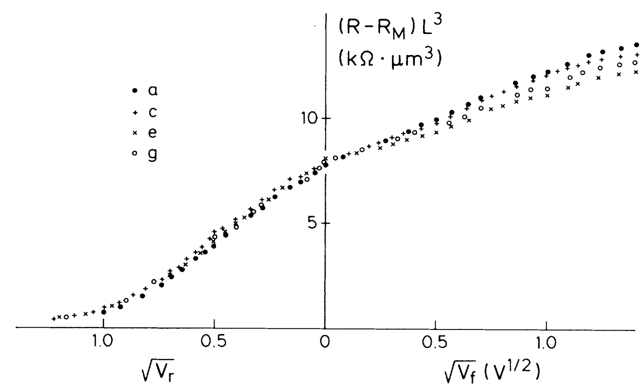

FIG. 2. Universal plot of the excess resistance above the Maxwellian spreading resistance, $R-R_M$, multiplied by L^3, versus $\sqrt{V}$. The symbols and letters a, c, e, and g refer to the same curves in Fig. 1.

ture, and $[n^+],[n]$ are the electron densities in the highly and lowly doped wedges.

Our data of Fig. 1 indicate that actually much larger resistances arise for this presumed forward polarity. Remarkably and unexpectedly, the resistance increases continuously as the positive voltage applied to the n wedge is increased.

Spenke's theory predicts[9,10] for high/low junctions an exponentially increasing forward current according to

$$I=I_S[\exp(qV/2kT)-1]\,, \tag{2}$$

and an essentially constant reverse current I_S for negative V, which was found to hold, e.g., for lowly doped, large-area germanium junctions.[9,10] Implicit in this theory is the neglect of any space-charge effects. The general theory of transport across such junctions is very complicated[9,11] and only tractable under simplifications, of which the assumption of "quasineutrality" is the most commonly employed. Minority-carrier supply is therefore postulated—and usually experimentally unavoidably realized—to neutralize any majority-carrier space charge; hence Eq. (2) can be deduced.[9,11]

In contrast, our experiments are designed to disclose the effects of space charge in small dimensions. We obtain a measure of contact diameter L by taking the resistance at $V=-2$ V to be essentially limited by the Maxwellian spreading resistance, R_M, according to Eq. (1). At this voltage, we attain an asymptotic value, free of space-charge effects, and we do not yet suffer from complications of hot-electron transport or avalanche multiplication seen at still higher electric fields. The nominal values of L are given for each of the six curves, selected from our data for Fig. 1.

The resistance $R-R_M$ in excess of the spreading resistance R_M can be represented by a universal plot, such as shown in Fig. 2. Our results indicate a proportionality

$$R-R_M\sim V^{1/2}L^{-m}\,, \tag{3}$$

where the exponent m depends somewhat upon doping, temperature, and range of L, and is $2\leq m\leq 3$.

We interpret this unipolar electronic transport behavior as dominated by space charge. At equilibrium, $V=0$, a space charge is formed by a thin layer of positive (arsenic) donor ions in the n^+ leg of the contact and a cloud of localized electrons extending to a depth of the order of a few Debye lengths ($L_D\approx 25$ nm for 300 K) in the n leg. Solution of Poisson's equation then yields the equilibrium energy barrier $q\phi_b$ of approximately 0.150 eV.

Application of a positive voltage V_f to the n leg reduces this barrier; electrons diffuse into the n leg. Their Coulombic excess charge can only be neutralized by the formation of a positive space charge of denuded donors downstream in the n leg. This depletion region constitutes the additional resistance $R-R(V=0)$. As V_f is raised, both amounts of charge are increased, and the space-charge-layer width w rises—thus the total resistance is increased—with the $w\sim\sqrt{V}$ dependence well known for abrupt junctions,[12] since most of the voltage drop arises across the depletion region and only a minor portion across the n^+/n interface due to this junction's exponential dependence of diffusion current on applied voltage. Negative voltages V_r lead to a barrier reduction by the electric field, analogous to the well-documented square-root dependence found in metal-semiconductor Schottky barriers.[13] The difference of the mechanisms leads to the different slopes seen for V_f compared with V_r in Fig. 2.

Our data of strictly unipolar transport thus show that here the previously accepted terminology of low-resistance "forward" and high-resistance "reverse" polarity for high/low junctions is no longer tenable and must be reversed. A troublesome inconsistency is then resolved, which arose when comparing current flow through contacts of an n-type semiconductor to an electron-rich metal (Schottky barriers) versus contacts to an electron-rich, more heavily doped semiconductor (high/low barriers). Unipolar n^+/n^- or p^+/p contacts thus behave qualitatively like metal-n or metal-p Schottky barriers in their polarity asymmetry of current transport.[8,12] We therefore have a new class of Schottky barriers, for which we propose the name *homojunction Schottky barriers,* composed of a differently doped portion of the same material. The barrier here arises not from a difference in work function[12,13] but from a doping-induced Fermi-level difference and ensuing space-charge effects. Such junctions constitute a simple, highly defined new object in the continuing quest to understand Schottky barriers, since the density of interface states can be made very low in such crystallographically continuous junctions.

We observe the described nonlinearities only in the limit of a "densely populated system,"[2,6] where the excess space charge approaches or exceeds the original equilibrium carrier densities by doping. The strong dependence upon dimensions L, as seen in Figs. 1 and 2, shows that we are dealing with a new effect exerted by geometrical size on the transport mechanism.

A quantitative theory of high/low junctions "presents formidable difficulties,"[14] the differential equation is third order and nonlinear, even for the unipolar case. Numerical methods[15] also rely on simplifications. Our case is further complicated by the wedge arrangement, which might be approximated by a spherical geometry, known for point-contact transport.[16] Nevertheless, the experimentally observed L^{-m} dependence of Eq. (3) and Fig. 2 shows that the additional resistance depends essentially on an injected space charge confined to a small volume of order L^3 and on a depleted region where current has to flow through a cross section of order L^2.

Experimental conditions have to be carefully controlled to reveal this nonlinear transport. Contacts with thin insulating interface layers show maximal resistance at $V=0$, decreasing symmetrically with voltage and indicating back-to-back Schottky barriers with electronic tunneling (see Fig. 6.12 of Ref. 8). We find such behavior for impure contact formation, especially at low temperatures and lower doping: We have carefully avoided this regime.

The large mechanical pressure at the small contacts is not an essential feature: Note that at the highest pressure (largest radii) we see the expected bulk Ohmic behavior, while the gently pressed junctions reveal the strongest nonlinearity. For higher applied voltages, we leave the diffusion-controlled regime and approach space-charge–limited conduction with the characteristic $I \sim V^2$ dependence.[16,17]

Our experiments relate to Landauer's concept[5,6] of strong spatial variations in the vicinity of a localized scatterer. His postulated "resistivity dipole," generated by an impressed current, resembles the dipole of electron pileup and electron depletion which is formed when we force a diffusive current across the resistivity discontinuity. Detection of phase-sensitive quantum effects requires lower temperatures and probably still smaller geometries.

In summary, we have shown that small semiconductor junctions of high doping versus low doping show unipolar electronic transport properties not previously observable in macroscopic samples. Such junctions at small size are neither the expected ideal contacts nor the high/low junctions, previously viewed under the restriction of assumed quasineutrality. Our samples rather look like a novel type of majority-carrier space-charge–dominated Schottky barriers.

We thank E. Gmelin and L. Weber for useful discussions and E. Bauser for skillful help with the sample preparation. We gratefully acknowledge a friendly critique from Rolf Landauer.

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