Quantized Electron Transport in Amorphous-Silicon Memory Structures

J. Hajto, A. E. Owen, S. M. Gage, and A. J. Snell
Department of Electrical Engineering, University of Edinburgh, Edinburgh EH9 3JL, Scotland

P. G. LeComber and M. J. Rose
Department of Applied Physics and Electronic and Manufacturing Engineering, University of Dundee,
Dundee DD1 4HN, Scotland

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Conduction in the ON state of amorphous-silicon memory devices is constrained to a narrow conducting filament. We present experimental evidence to show that the memory ON state is associated with quantized electron transport which is presumably related to quantum confinement effects in the small conducting filament. Current-voltage characteristics of typical ON states exhibit discrete steps which correspond to quantized resistance states and the steps split appropriately in a magnetic field. An especially notable feature is that the quantization can be observed at relatively high temperatures (up to ~190 K).

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We have previously shown that amorphous-silicon metal-p^+-n-i-metal and metal-p^+-metal junctions exhibit nonvolatile, polarity-dependent digital and analog memory-switching phenomena after initial conditioning by means of a moderately high applied potential ("forming").[1-4] An essential feature of this forming process is the creation of a filamentary region of highly conducting material. In the ON state the current is carried primarily through this region, which is much less than 1 μm in diameter. Experimental evidence for filamentation comes from studies of the ON-state resistance, which show R_{ON} to be independent of area, by thermal imaging with liquid crystals, and by direct observation with a scanning electron microscope combined with microanalysis. The latter technique indicated that the formation of the current filament is associated with local diffusion of the top metal contact into the amorphous silicon, resulting in a region of mixed or "alloyed" metal and silicon. More recent experimental work has resulted in a new metal-p^+-metal amorphous-silicon device which, rather than exhibiting two-state digital operation, has a continuum of stable conductance states which are nonvolatile and fully programmable by single 10-ns voltage pulses.[4] These new analog memory devices have applications as nonvolatile, reprogrammable memory elements in analog neural networks. In this paper we present new results showing that the current-voltage characteristics of such structures at low temperatures exhibit steplike features associated with quantized transport.

The samples used for this work were amorphous-silicon Cr-p^+-V sandwich structures configured as shown in Fig. 1. The 1000-Å-thick p^+ amorphous-silicon layer was prepared by rf-glow-discharge decomposition of SiH_4 containing 10^4 ppm by volume of B_2H_6, with the contact area defined by a 10-μm-diam pore in an insulating layer. The top and bottom metal electrodes were prepared by vacuum evaporation. By applying 300-ns voltage pulses of progressively increasing magnitude, the resistance of the as-prepared device can be gradually lowered from 10^9 Ω to $\sim 10^3$-10^4 Ω. After this initial forming step, all subsequent memory-switching operations can be performed with 10-100-ns pulses, 1.5-5 V in magnitude. Under these conditions the devices exhibit fast analog switching;[4] i.e., they show a continuum of nonvolatile states with resistances ranging from $R_{\mathrm{ON}} = 10^3$ Ω to $R_{\mathrm{OFF}} = 10^6$ Ω. In the present work we have studied the low-temperature conductivity behavior of the devices in a range of such analog memory states.

Typical current-voltage characteristics of a formed memory ON state measured at 4.2 K are shown in Fig. 2. In the voltage region from 0 to 0.37 V, the current in-

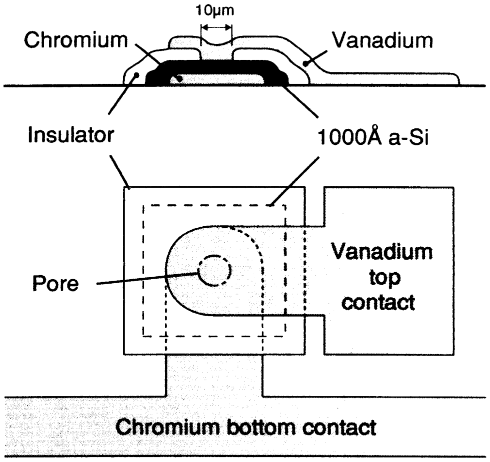

FIG. 1. Structure of the amorphous-silicon device.

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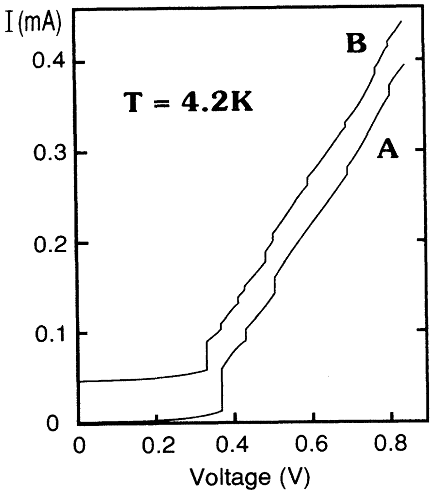

FIG. 2. *I-V* curves at 4.2 K with and without magnetic field. Curve *B* has been offset by 50 μA on the current scale for clarity.

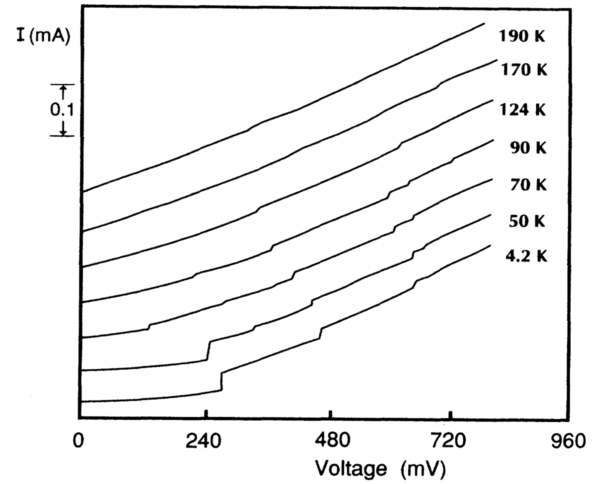

FIG. 3. *I-V* curves as a function of temperature. The curves have been offset on the current scale for clarity.

creases continuously in a non-Ohmic manner. At a critical voltage $V_{\rm cr}$, in this instance at 0.37 V, there is a distinct change in the behavior of the sample. A sudden current jump occurs at this point and the resistance of the sample is lowered to the order of a few kΩ. After the first current jump at 0.37 V, further current steps can be observed at 0.43, 0.51, 0.70, and 0.81 V (curve *A* in Fig. 2). The current-voltage characteristics are symmetrical about the origin.

Curve *B* in Fig. 2 depicts the current-voltage characteristics of the same sample under the influence of a 0.2-T magnetic field. The curve has been displaced by 50 μA on the current scale for clarity. The direction of the magnetic field is 30° with respect to the filament. Further steps can now be observed at 0.33, 0.41, 0.49, 0.60, and 0.78 V in addition to those observed in the zero-magnetic-field case (curve *A*). The effect of the magnetic field is completely reversible. Similar *I-V* characteristics have been obtained for a range of samples with varying initial resistance states. The critical voltage $V_{\rm cr}$ at which the first current jump occurs and the amplitude of this first current jump are dependent on the resistance of the memory ON state investigated. After the first jump, however, the characteristics for each sample investigated lie on a similar curve, suggesting a similar conduction mechanism at voltages above $V_{\rm cr}$.

Figure 3 shows the effect of temperature on the current-voltage characteristics of a different sample from the one shown in Fig. 2. The curves have been shifted along the current axis for clarity. The magnitude of the current steps gradually decreases with increasing temperature until the effect is no longer observable at ~190 K. Figure 4 shows the data for curve *A* in Fig. 2 replotted to show resistance as a function of applied voltage. The steps in the current are clearly seen to be associated with a quantized resistance $R=h/2ie^2$, where i is an integer. In the voltage range from 0.3 to 0.8 V, there are five steps in the current in curve *A*, Fig. 2, corresponding to values for i of 2, 3, 4, 5, and 6. Higher voltages have not been applied to the sample because these could change the resistance of the particular memory state. With a magnetic field applied to the same sample further quantization of resistance is observed at values $R=h/2(i+\frac{1}{2})e^2$. Theoretical considerations predict that the steps should be flat, as shown by the dashed lines in Fig. 4. That they are not flat in the present results is thought to be due to the presence of a parallel conduction path through the bulk of the amorphous silicon around the filament. Figure 5 shows that a sample in a given resistance state exhibits reproducible behavior at low temperatures even after thermal cycling. Curves *a* and *b* show

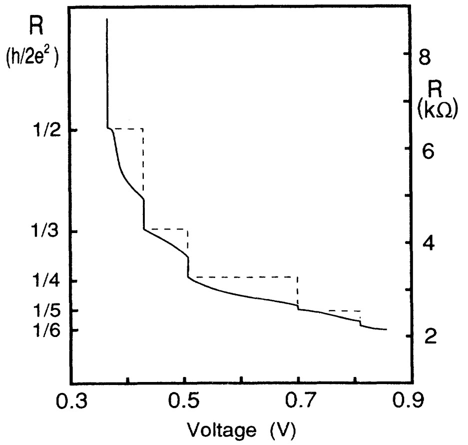

FIG. 4. Resistance vs voltage at 4.2 K with no magnetic field. The dashed line indicates the behavior predicted by theory.

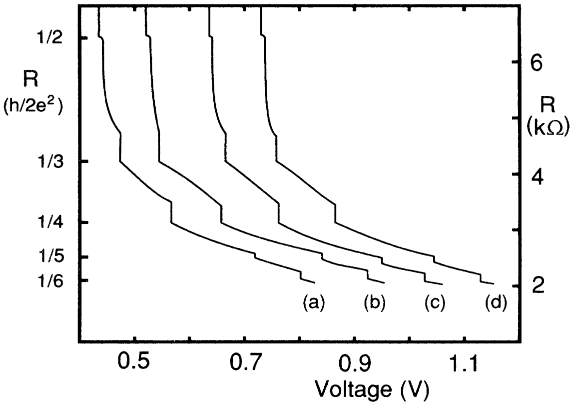

FIG. 5. Reproducibility of resistance characteristics before and after thermal cycling. Curves are offset by 0.1 V on the voltage scale for clarity.

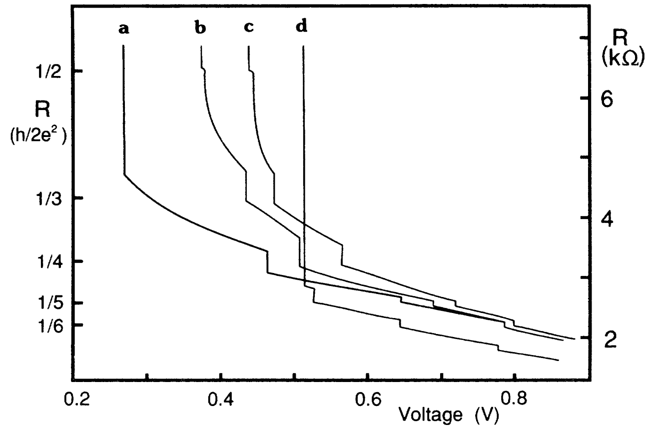

FIG. 6. Reproducibility of the resistance-voltage characteristics obtained on different samples.

the electrical characteristics of a sample at 4.2 K with a delay of several hours between measurements. Curves *c* and *d* show measurements on the same sample after temperature cycling between room temperature and 4.2 K.

Figure 6 shows the reproducibility of the observed quantized resistance jumps for four different samples (denoted by *a*, *b*, *c*, and *d*). (Curve *a* was obtained by replotting the current-voltage characteristics in Fig. 3 at 4.2 K.) These curves represent the largest deviation among the samples measured—the resistance-voltage curves of all of the other samples measured lay within these values. It is important to note that in this case there is no offset between the curves; i.e., they are directly replotted from the measured current-voltage characteristics. The critical voltage V_{cr} and the voltage values at which the quantized resistance jumps occur are different for the different samples but the quantized jumps are always very close to the values of the quantized resistance $R=h/2ie^2$. The typical deviations are $\pm 2\%$ at $i=2$, $\pm 2.5\%$ at $i=3$, $\pm 6\%$ at $i=4$, $\pm 4\%$ at $i=5$, and $\pm 4\%$ at $i=6$. The first jump, however, occurs from $R=15200\ \Omega$ to $4820\ \Omega$ in curve *a*, which is apparently a 12% deviation from the quantized resistance value of $R=4291\ \Omega$ (at $i=3$). Also, in the case of curve *d*, the resistance jumps first to $R=4820\ \Omega$ at $V_{\mathrm{cr}}=0.51$ V followed by another closely spaced jump (at $V=0.525$ V) to $R=2550\ \Omega$, which is very close to the quantized value of $R=2575\ \Omega$ (at $i=5$). These relatively large discrepancies are always associated with the ***first*** current jump in the I-V characteristics at V_{cr}, and hence with a change in the conduction mechanism. This first transition at V_{cr} might not be expected to occur therefore at a voltage corresponding to a change in quantized resistance value.

The experimental data presented above show that we have observed discrete steps in the I-V characteristics for the ON state of amorphous-silicon Cr-p^+-V structures which are associated with a quantized resistance. The current-voltage characteristics (see Fig. 2) indicate that the filament has a relatively large resistance around zero bias. Such an anomalously high zero-bias resistance in metal/amorphous-silicon/metal structures was recently shown to be consistent with the assumption that electron transport in the filament at low bias is dominated by tunneling between small metallic particles embedded in a dielectric medium (presumably amorphous silicon).[3] We assume that the conducting filament is composed of two parts—small-scale inclusions of permanently changed material connected by conducting channels which are formed, broken, dimensionally changed, reformed, etc., during switching. The evidence is that the overall diameter of the filament at the top contact is $\ll 0.5\ \mu\mathrm{m}^2$. The length of the channels must be consistent with tunneling. With increasing applied voltage, the tunneling current increases exponentially. This implies that at the critical voltage V_{cr}, the tunneling barrier effectively "breaks down" and a much larger current flow occurs. This is not a destructive effect as the process is completely reversible and no material changes ensue. Assuming that the metallic inclusion has a curved shape, the current flow would be restricted to a ***very localized area.*** The observation of quantized resistance suggests that the channel can be considered to be an electron waveguide with confinement being brought about by the combination of the applied field and the geometry and constitution of the conducting filament.

There is a wide range of experimental and theoretical work on electrical transport through quantum point contacts.[5] These are short and narrow constrictions in a two-dimensional electron gas, with a width of the order of the Fermi wavelength λ_F. Because of the high mobility, elastic impurity scattering and inelastic scattering are negligible and therefore the mean free path of the electrons is longer than the length of the conduction channel. In this case ballistic transport takes place and the resistance of such quantum point contacts is quantized in units of $h/2e^2$. The notion of a very small conducting filament in the amorphous silicon devices being made up of metallic inclusions has similarities to the idea of quantum point contacts and it is possible, therefore, that the quantized resistance states described here are a result of the same sort of mechanism. The crucial question is whether ballistic transport is possible in the amorphous-silicon device. Carrier mobilities in amorphous silicon are normally trap limited and are orders of magnitude lower than expected for ballistic behavior (e.g., $\sim 10^{-2}$ $\mathrm{cm^2\,V^{-1}sec^{-1}}$). It is worth noting, however, that we have previously estimated a carrier mobility as high as 100 $\mathrm{cm^2V^{-1}sec^{-1}}$ from magnetoresistance measurements on devices similar to those used in the present experiments and that mobility is certainly related to the conducting filament rather than the "bulk" amorphous silicon.[4] On the other hand, it is entirely unexpected that quantized resistance states associated with ballistic transport should be observed when, as in the present case, the applied voltage is greater than kT (or greater than the spacing between subbands).[6,7] At the moment, therefore, the issue is unresolved and it is not realistic to speculate further about mechanisms except to note that the observed quantized transport effects suggest the importance of the dimensions of the conducting channel rather than material parameters. The significance of using amorphous-silicon devices lies in the forming process which promotes the formation of very small features which then dominate conduction.

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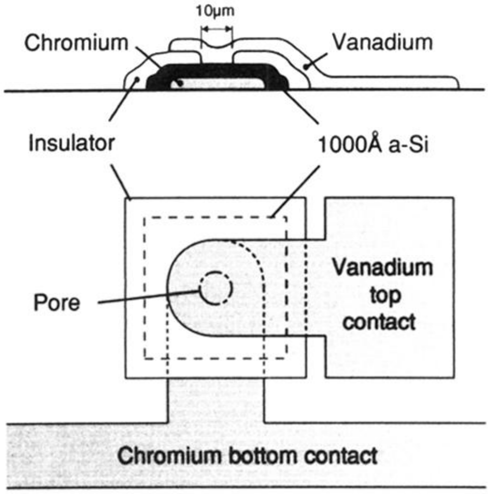

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