Quantum point contact switch realized by solid electrochemical reaction

Kazuya Terabe,[*1,*2,†] Tsuyoshi Hasegawa,[*1,*2] Tomonobu Nakayama,[*1,*2] and Masakazu Aono[*1,*2,*3]
[*1] *Surface and Interface Laboratory, RIKEN*
[*2] *CREST, Japan Science & Technology Corporation*
[*3] *Department of Precision Science and Technology, Osaka University*

The formation and annihilation of a quantum point contact (QPC) are controlled by a solid electrochemical reaction. A silver nanotip grows on a silver sulfide (Ag_2S) electrode to build an atomic bridge to a Pt electrode at a distance of 1 nm. Since the growth and shrinkage of the silver nanotip are controlled simply by applying a certain bias between the two electrodes, it can be used as a switching device.

Introduction

Quantum conductance in metallic nanowires has been extensively investigated since the first report of an experiment using a gold nanowire.[1] Nanowires showing conductance quantized in units of $(2e^2/h)$ have been formed by contacting two electrodes using mechanical positioning systems such as a scanning tunneling microscope (STM).[2–5] Recently, a combination of a STM and a transmission electron microscope (TEM) has enabled the simultaneous observation of the atomic structure of a nanowire and measurement of its quantized conductance,[6,7] which provides useful information for a theoretical approach to understanding the mechanism of a quantum point contact (QPC). A QPC switch has been demonstrated by repeatedly bringing a sharpened metallic wire into contact with a gold surface using a STM.[8]

In the previous experiments, QPCs were achieved using a mechanical positioning system, but the QPCs appear for only a short time, typically 1 second, while the two electrodes are in contact. Therefore, making the QPC stable and controlling its conductance require a feedback control system such as that used in a STM.[8] However, in view of introducing QPCs into actual devices, it is not feasible for each QPC, namely, each 'bit,' to employ its own feedback control system containing large circuits. Using a mechanical positioning system such as a piezodevice is also undesirable from the viewpoint of integrating devices.

We developed a new type of QPC, which is formed by a solid electrochemical reaction. Since it works without a mechanical positioning system and its conductance is controlled simply by applying a certain bias to it, this QPC is easily introduced into actual devices. Here, we review the new QPC, particularly its function as a switching device.

Principle of the QPC

In the present study, a silver wire covered by silver sulfide (Ag_2S) crystal, which is a mixed ionic and electronic conductor, is used as one of two electrodes. The other electrode (Pt) is set at a distance of 1 nm from the Ag_2S electrode. When a negative bias is applied to the Pt electrode with respect to the Ag_2S electrode, silver ions in Ag_2S are neutralized to silver atoms by electrons flowing from the Pt electrode, resulting in the precipitation of the silver atoms at the surface of Ag_2S, as shown in Fig. 1(a). Between the two electrodes, the silver atoms form an atomic bridge whose conductance can be quantized.[9] Since silver atoms in the silver wire are ionized and dissolved into the bulk of Ag_2S at the same time, the density of silver ions in the Ag_2S crystal scarcely changes, which results in the stability of the atomic bridge. When the opposite bias is applied, silver atoms in the bridge are ionized and dissolved into the bulk of Ag_2S, as shown in Fig. 1(b), which results in the thinning and breaking of the bridge. In this manner, the formation and annihilation of the QPC can be controlled by applying a bias between the electrodes.

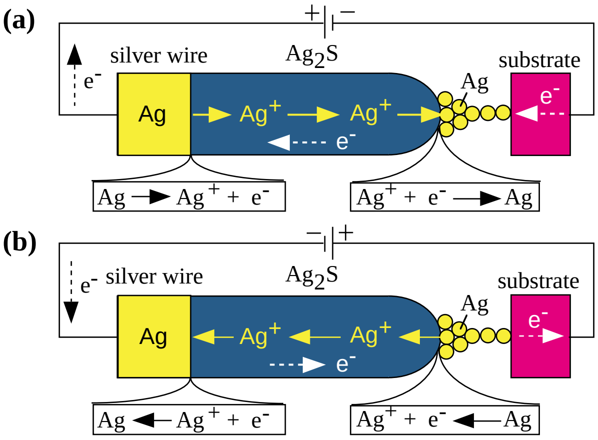

Fig. 1. Principle of a QPC switch formed by a solid electrochemical reaction. (a) Formation process and (b) annihilation process of the QPC.

Experimental

Ag_2S single crystal was prepared by the reaction of a silver wire with sulfur vapor.[10] Although we confirmed that the QPCs work in both vacuum and air,[9] all results reported here were obtained in experiments performed in vacuum. An

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[†] Present address: National Institute for Materials Science

ultrahigh vacuum (UHV) STM was used for the experiments in vacuum. Needlelike single crystals of Ag_2S with lengths of 0.1–0.5 mm grown at the end of a silver wire were used as STM tips, namely, each formed one electrode. A chemically polished Pt sheet was resistively heated to 1000°C in the UHV chamber and was used as a sample, namely, the other electrode.

First, the tip was brought sufficiently close to the sample so that a tunneling current flowed between them with a bias lower than the threshold bias of QPC formation and annihilation.[10] Then, the tip position was fixed and the formation and annihilation of the QPC were controlled simply by changing the bias between the tip and the sample.

Controlled formation and annihilation of the QPC

When a negative bias is applied to a Pt sample with respect to a Ag_2S tip, a silver atomic bridge is formed between them, and the bridge disappears when the opposite bias is applied. Upon repeatedly changing the polarity of the bias, a cyclic appearance and disappearance of the QPC can be observed.

Figure 2 shows three cycles of this phenomenon, which continues infinitely. The bias applied to the Pt sample was swept repeatedly from positive to negative and vice versa, as indicated by the arrows in the figure. When the bias became negative, silver atoms started to precipitate, forming an atomic bridge between the Ag_2S tip and the Pt sample. A sudden decrease in the resistance of the QPC indicates the completion of bridge formation. When the bias became positive, the thinning of the bridge led to an increase in the resistance of the QPC. Finally, the bridge disappeared, as indicated by the sudden increase in the resistance of the QPC. This cyclic formation and destruction of the bridge can continue infinitely.

Using binomial biases, the QPC functions as a switching device. Figure 3 shows an example in which +500 mV and −500 mV were applied to a sample alternately at 100 kHz. Since +500 mV and −500 mV are much higher than the threshold biases of bridge formation and destruction, these phenomena occurred immediately when the bias was changed. Namely, when the negative bias was applied to the sample, the resistance of the QPC immediately decreased to 2–3 kΩ due to bridge formation. When the positive bias was applied to the sample, the resistance rapidly increased to 20 kΩ due to bridge destruction. Switching between conductances quantized in units of $(2e^2/h)$ has also been demonstrated using a certain bias.[9] The QPC switch is expected to operate at 100 MHz, on the basis of the growth rate of the silver nanotip.

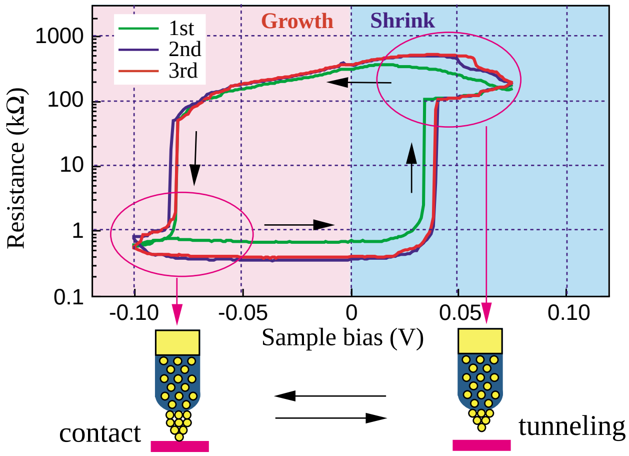

Fig. 2. Cyclic formation and destruction of the bridge.

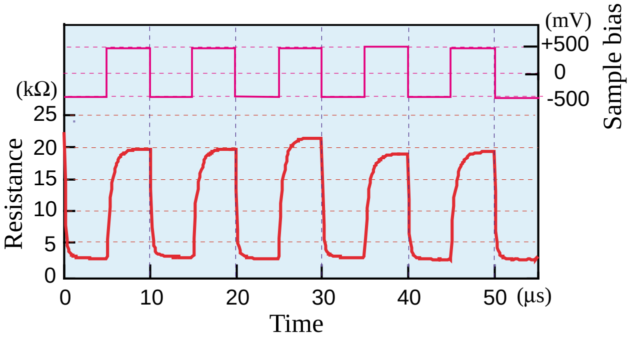

Fig. 3. Switching at 100 kHz.

Conclusion

A quantum point contact (QPC) switch was realized by a solid electrochemical reaction. The growth and shrinkage of a silver nanotip at the apex of a Ag_2S tip were controlled simply by applying a bias between the tip and a Pt sample. The QPC has the function of switching which can be used in actual devices.

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