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Resonant electron tunneling in single quantum well heterostructure junction of electrodeposited metal semiconductor nanostructures using nuclear track filters

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Abstract

We report on resonant electron tunneling through a Cu–Se heterostructure junction grown electrochemically in the submicron size pores (0.8 μm) of a nuclear track filter (Polycarbonate). The prominent feature of negative differential resistance (NDR) has been observed in the current–voltage (*I–V*) characteristic of the so-fabricated array of resonant tunneling diodes (RTDs) even at room temperature, along with a significant peak to valley current ratio (2.5) of the resonance. Tunneling structures of the nanofabricated RTDs around zero bias are also observed at room temperature. Our results show that the low cost and relatively easy electrodeposition method can be a very effective way to prepare resonant quantum tunneling devices, using the pores of nuclear track filters.

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Keywords: Nuclear track filters (NTFs); Swift heavy ions (SHI); Electrodeposition; Resonant tunnel diodes (RTDs)

1. Introduction

The technological importance of Nuclear Track Filters (NTFs) is very large due to the various potential applications particularly in the field of micro/nanostructure electronic device fabrication. In recent years, there has been tremendous interest in nanopores and micropores in polymers, generated by swift heavy ions (SHI) due to a vast variety of applications [1,2]. These pores are created by controlled chemical etching of ion-irradiated thin polymer foils, so as to produce NTFs. Physical properties of a material can change significantly in the transition between

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the macroscopic scale and the nanoscale. Therefore, nanophysics fabrication is very important both for its technological application and fundamental interest. The possibility of resonant tunneling in a zero-dimensional quantum well has been the subject of intense research over the years, since the first work by Reed et al. [3]. Functional devices based on resonant tunneling through double barrier heterostructures are of much promise in a variety of applications such as digital and analog circuits. However, a single barrier structure being easy to fabricate and of better high-frequency response is also of much interest. To date, most of the research on small area resonant tunneling devices has employed AlGaAs–GaAs heterostructure semiconducting material systems, which have been grown by Molecular Beam Epitaxy (MBE) technique followed by reactive ion etching [4–6]. Fabrication of resonant tunnel devices using the MBE technique has certain limitations as reactive ion etching can introduce damage at the device side wall surface [7]. However, recent advances in electrodeposition technique make possible the growth of well-defined periodic structures, such as magnetic multilayers with layer thicknesses as small as few nanometers [8]. Chakarvarti et al. [9,10] recently employed this relatively easy and versatile electrodeposition technique to grow microstructure metal-semiconductor heterostructure junctions using the novel material system Cu–Se in the chemically etched pores of polycarbonate foils. The first and preliminary investigation on this entirely new and until now unpublished material system demonstrated characteristic feature for the formation of a microstructure resonant tunneling diode [10]. In this paper, we present results of our detailed investigation on the array of low-dimensional resonant tunneling diodes (RTD), fabricated by controlled electrodeposition of Cu–Se in the nanopores of a swift heavy ion-irradiated polycarbonate foil. We also demonstrate a low-cost resonant tunneling device as a result of a metal semiconductor (Cu–Se) single barrier heterostructure, which provides negative differential resistance (NDR) characteristic with high peak to valley current ratio (PVR) even at room temperature.

2. Experimental details

The NTFs used in the present work were of Makrofol KG (polycarbonate from Bayer AG), 10 μm thick, having an average pore diameter of 800 nm with pore density 10^6 cm^{-2}. These were prepared by irradiating the foils with heavy ions (^{28}Si, 100 MeV with ion fluence 10^6 ions/cm^2) at the 15 MV pelletron accelerator of the Nuclear Science Centre (NSC) [11] New Delhi, India, using the General purpose scattering chamber (GPSC) facility and followed by chemical etching of the latent tracks in 6.25 N NaOH, at 60°C for 40 min. These are known to be the optimum conditions to produce etched-through pores. For electrodeposition, a suitable cell is designed and fabricated. The design of the cell used in the present work, is shown in Fig. 1. For the fabrication of Cu–Se heterostructures, the cathode of the cell was covered with the processed NTF (a circular disc. with diameter 0.01 m) as shown in Fig. 1. The electrolyte $CuSO_4 \cdot 5H_2O$ acid solution (7.5 mg $CuSO_4 \cdot 5H_2O$ in 40 ml distilled water i.e. 0.65 M+0.5 ml of 25% dil. H_2SO_4) was used first to deposit Cu. A current density of 0.03 A cm^{-2} was applied for 20 min, using a transistorized regulated d.c. power supply. Assuming that after this inter-

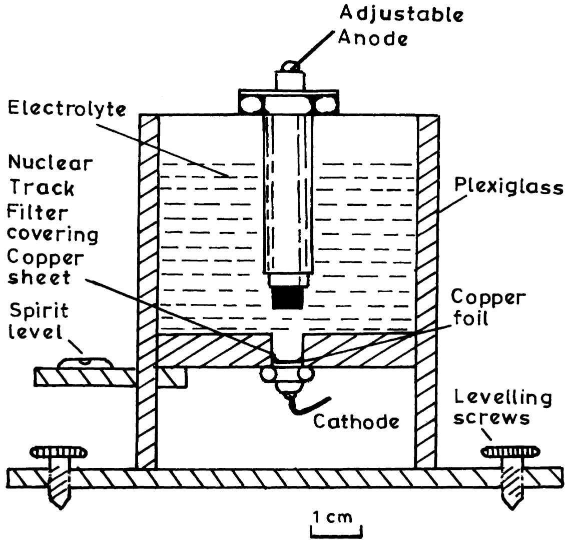

Fig. 1. Design of the electrodeposition cell.

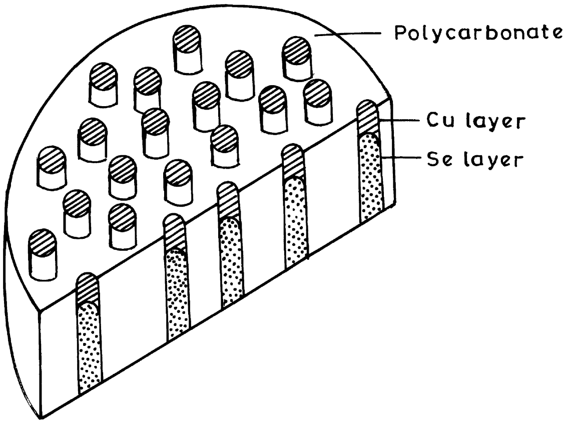

Fig. 2. Schematic representation of the array of RTDs formed in the insulating polymer matrix.

val, the electrodeposition should have approximately half filled the pores, the first electrolyte was drained off and a second electrolyte having a composition of SeO_2 (9×10^{-4} M) with 0.5 ml of 35% dil. H_2SO_4 was introduced in the cell. A current density of 0.03–0.06 A cm^{-2} was again allowed to pass for 30 min. Acid solution of the electrolyte SeO_2 (9×10^{-4} M) was used because of its outstanding microthrowing and covering power i.e. ability to deposit selenium into holes at relatively low current density. As soon as the plating process was over, the NTF foil was carefully removed, washed with distilled water and ethanol and air-dried. On the respective sides of the NTF, two layers of Cu and Se could be seen. Fig. 2 shows a schematic representation of the array of RTDs formed in the insulating polymer matrix.

3. Results and discussion

Fig. 3(a) and 3(b) show the scanning electron microscopy (SEM) pictures of the array of several RTDs fabricated as metal semiconductor nanostructures using NTF. For this SEM picture, the polymer matrix was dissolved in a suitable organic solvent, leaving behind the metal semiconductor nanostructure. Fig. 3(a) is the lateral view of several nanofabricated RTDs, in which the upper layer is copper and the lower layer is selenium. It seems that the polymer matrix is not fully removed by the organic solvent. Fig. 3(b) shows the top view of the array of the so-fabricated RTDs. It clearly shows that the structures are not hollow, i.e., they are filled completely with solid material. For the current–voltage (*I–V*) characteristic of the nanostructured RTDs (device diameter: 800 nm), an ohmic contact was made using a gold contact tip (5 μm diameter) on top of the selenium side of the NTF. The copper side of the NTF was placed on a brass plate, and the whole assembly was then connected to a Keithley source measure unit (model 236). Fig. 4 represents the *I–V* characteristic of the RTDs taken at two different points of the NTF as measured at room temperature. Both curves show the prominent negative differential resistance (NDR) regions, even at room tempera-

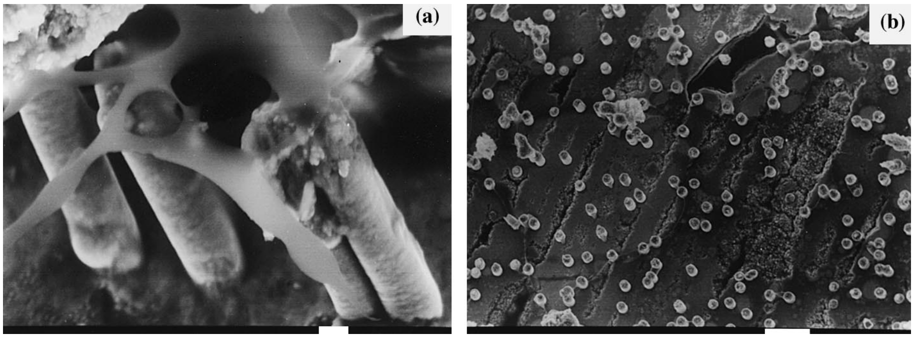

Fig. 3. Scanning electron micrographs of the ensembles of electrochemically grown Cu–Se submicron-size structures (0.8 μm) using the pores of Macrofol KG nuclear track filter. (a) Lateral view of nanofabricated RTDs with bar length of 400 nm. (b) Top view of the array of RTDs, showing the nanostructures are not hollow. Bar length is 4 μm.

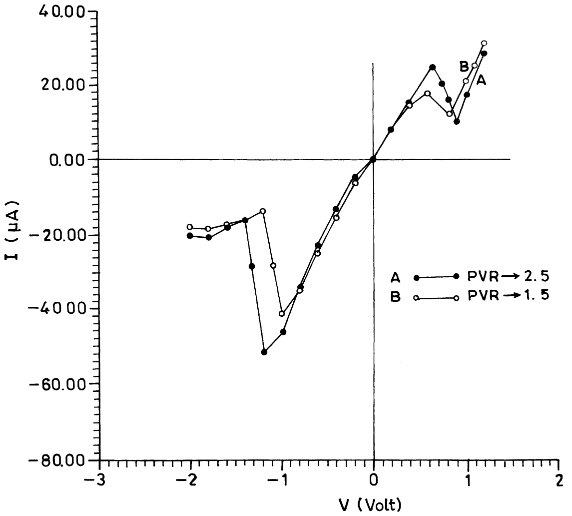

Fig. 4. Current–voltage (*I–V*) characteristics of the electrochemically grown submicron-size RTDs using the pores of NTF, at room temperature. (A) and (B) show the (*I–V*) curves of two different RTDs, taken at two different points of the NTF along with the corresponding peak to valley current ratios (PVR).

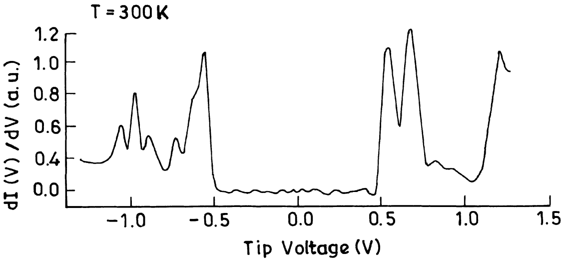

Fig. 5. Tunneling structures of the electrochemically grown RTDs using the submicron-size pores (0.8 µm) of NTF around zero bias, taken at room temperature.

ture. This is a significant result obtained from our fabricated single barrier RTDs, using the novel material system Cu–Se. The *I–V* characteristic curves A and B also show a high peak to valley current ratio (PVR). The forward biasing resonance in curve A occurs at 600 mV, with 2.5 as PVR, whereas in the curve B the resonance takes place at 550 mV, and with 1.5 as PVR. The partly lacking reproducibility of the curves measured at different points of the NTF may be attributed to the following reasons. It may be possible that, some of the RTDs have greater Cu concentration than Se concentration and viceversa. Moreover, the RTDs formed in that way do not exactly match each other in the Cu–Se concentration profile. This is one of the limitation of the electrodeposition technique. However, the nature of the *I–V* characteristic taken at any point of the NTF was found to be similar. To check the material property in the macroscopic scale of the Cu–Se combination, selenium was electrodeposited onto a copper tape and the *I–V* behavior was found to be nearly metallic. The absence of pure rectifying characteristic of a metal-selenium contact may be due to the electrodeposited impure material system. Nevertheless, it is confirmed that the phenomenon of resonant electron tunneling in the nanostructured material system Cu–Se is primarily a low-dimensional property. It can be seen from the curves A and B, that the valley regions of the current are almost negligible, thereby giving the significant PVR ratio. The insignificant valley current is interpreted as due to the minimum thermally activated surface current, in the nanometer scale RTD devices, as reported earlier [12]. Fig. 5 shows a $dI(V)/dV$ versus V curve at room temperature for an RTD fabricated in the way described above, which represents tunneling spectroscopy around zero bias. Interestingly, our RTD characteristics show close resemblance to the structures obtained by Nomoto et al. [12] and Tehrani et al. [13], where particularly the authors of Ref. [13] described three-terminal resonant interband tunneling FET (RITFET), based on type II InAs/AlSb/GaSb RITD integrated into the drain or source region of InGaAs/AlGaAs/GaAs FET. This shows the possibility of combining the RTD structure obtained in our case with the best of FET technology to achieve the highest possible peak to valley current ratio and gain for future three terminal quantum devices. Further it will also be interesting to study the device diameter dependence on the RTD characteristics obtained in our case. For this purpose the pore size of the NTF will be varied, down to a few nanometers by selective etching conditions. Work is under progress in our laboratory to further optimize the experimental parameters for studying the tunneling structure of the fabricated RTDs using different pore sizes of NTF at low temperature.

4. Conclusion

In conclusion, we report here on the observation of resonant tunneling in a Cu–Se single barrier/single quantum-well heterostructure junction produced electrochemically in the nanopores of nuclear track filter NTF (polycarbonate). We have demonstrated that in comparison to the high cost molecular beam epitaxy system, the easy and cheap electrodeposition technique can be a very effective way to prepare resonant electron tunneling devices using nanopores of NTFs. The current voltage characteristic of RTDs fabricated in that way have shown very significant results. Prominent features of the negative differential resistance region (NDR) along with significant peak to valley current ratio (PVR) (2.5) could be observed even at room temperature. Besides this, tunneling structures around zero bias of the nanofabricated RTDs are also observed at room temperature. However, we could not yet obtain good reproducibility in the *I–V* characteristics of submicron size (0.8 μm) RTDs in our case. This may actually be attributed to the uneven Cu–Se concentration profile of the fabricated diodes, which could be possibly rectified by further optimization of the electrodeposition parameters, viz. the current density, etc. Nevertheless, the results obtained are encouraging and demand for further investigations using the versatile electrodeposition technique.

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