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## Phase-slip Events in MoRe-Si(W)-MoRe heterostructures

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## Abstract

Recently, quantum phase slips in nanowires and nanoscale superconducting heterostructures, which are potential devices for THz radiation sources and detectors, have received a great deal of interest [1,2]. Phase slip centers (PSCs) may emerge in a uniform wire if its width  $d$  is smaller than the coherence length. The order parameter in a PSC becomes equal to zero whenever the phase difference across the PSC increases by  $2\pi$ . In close similarity to weak links and Josephson junctions, the phase slippage frequency is given by the Josephson relation [3].

MoRe-Si(W)-MoRe-Si(W)-MoRe structures are fabricated by magnetron sputtering of MoRe and combined Si(W) targets in argon ( $P \sim 0.1$  Pa), followed by the deposition of thin films through a metal mask onto a polycrystalline  $\text{Al}_2\text{O}_3$  wafer. Tungsten (W) quantum dots are formed within the deposited silicon layer during the joint deposition of Si and W due to a self-organizing effect. Space charges are localized in the amorphous silicon layers forming potential barriers with traps for the charge transport.

## Discussion

- $\text{SiO}_x(\text{W})$  barriers contain a quasi-periodical two-dimensional net of tungsten nanoclusters which can be considered as a net of nanorods in the non-conducting Si matrix, as was evidenced by AFM images obtained in a non-contact operation mode.
- $I$ - $V$  curves of the MoRe-Si(W)-MoRe heterostructures have revealed an occurrence of inclined current steps induced by applied external microwave radiation; their shape and position depend on the power level of the radiation. It puts in light the emergence of phase-slip centers (PSCs) in the heterostructures.
- The resistance of the heterostructures follows the  $R_d = R_{d1} n$  formula where  $R_{d1}$  is the differential resistance of the linear region of the  $I$ - $V$  characteristic corresponding to the first phase-slip center;  $n$  is the PSC number.
- The appearance and behavior of the steps [4] demonstrate that, for a heterostructure supercurrent exceeding a certain critical value  $I_c$ , the regime of the Cooper pair transport (supercurrent) through bound Andreev states has been changed by the PSCs emergence in the tungsten clusters. As a result, such heterostructures can be understood as a net of dynamically created Josephson junctions [5].
- The four-terminal hybrid superconductor - semiconductor (with quantum dots) - superconductor - semiconductor (with quantum dots) - superconductor devices have been fabricated and their  $I$ - $V$  curves have been measured experimentally.
- The  $I$ - $V$  curve of a middle MoRe film in a four-terminal heterostructure has revealed the emergence of current-induced inclined current steps.
- The heterostructures demonstrated a switching effect: the voltage value can be controlled by changing the control current value which induces the PSC appearance and, as a result, the heterostructure  $I$ - $V$  curve can be controlled.

### References

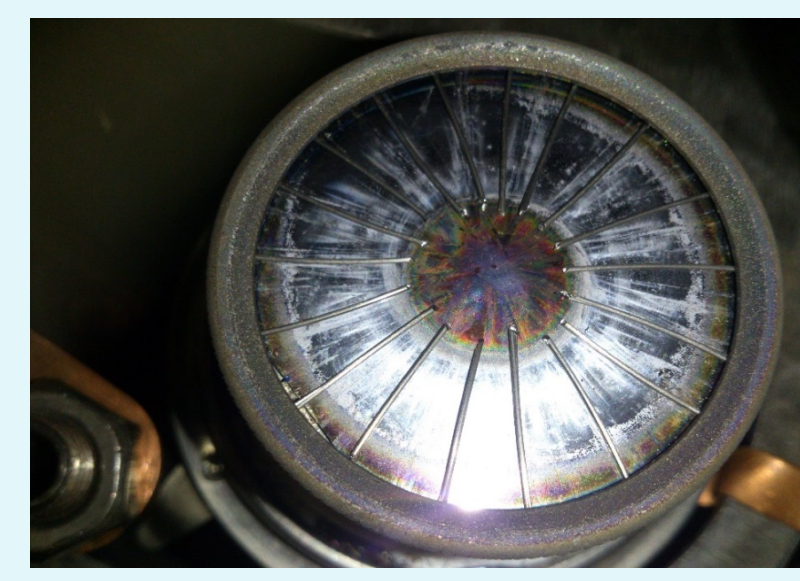
- [1] S. Savel'ev *et al.*, *Rep. Prog. Phys.* 73, 026501 (2010).
- [2] U. Welp, K. Kadowaki, and R. Kleiner, *Nature Photonics* 7, 702 (2013)
- [3] V.I. Kuznetsov and V.A. Tulin, *Sov. Phys. JETP* 86, 1364 (1998).
- [4] V.E. Shaternik *et al.*, *IEEE Trans. Appl. Supercond.* 27, 1800507 (2017).
- [5] A.G. Sivakov, A.M. Glukhov, and A.N. Omelyanchouk, *Phys. Rev. Lett.* 91, 267001 (2003).

## Acknowledgments

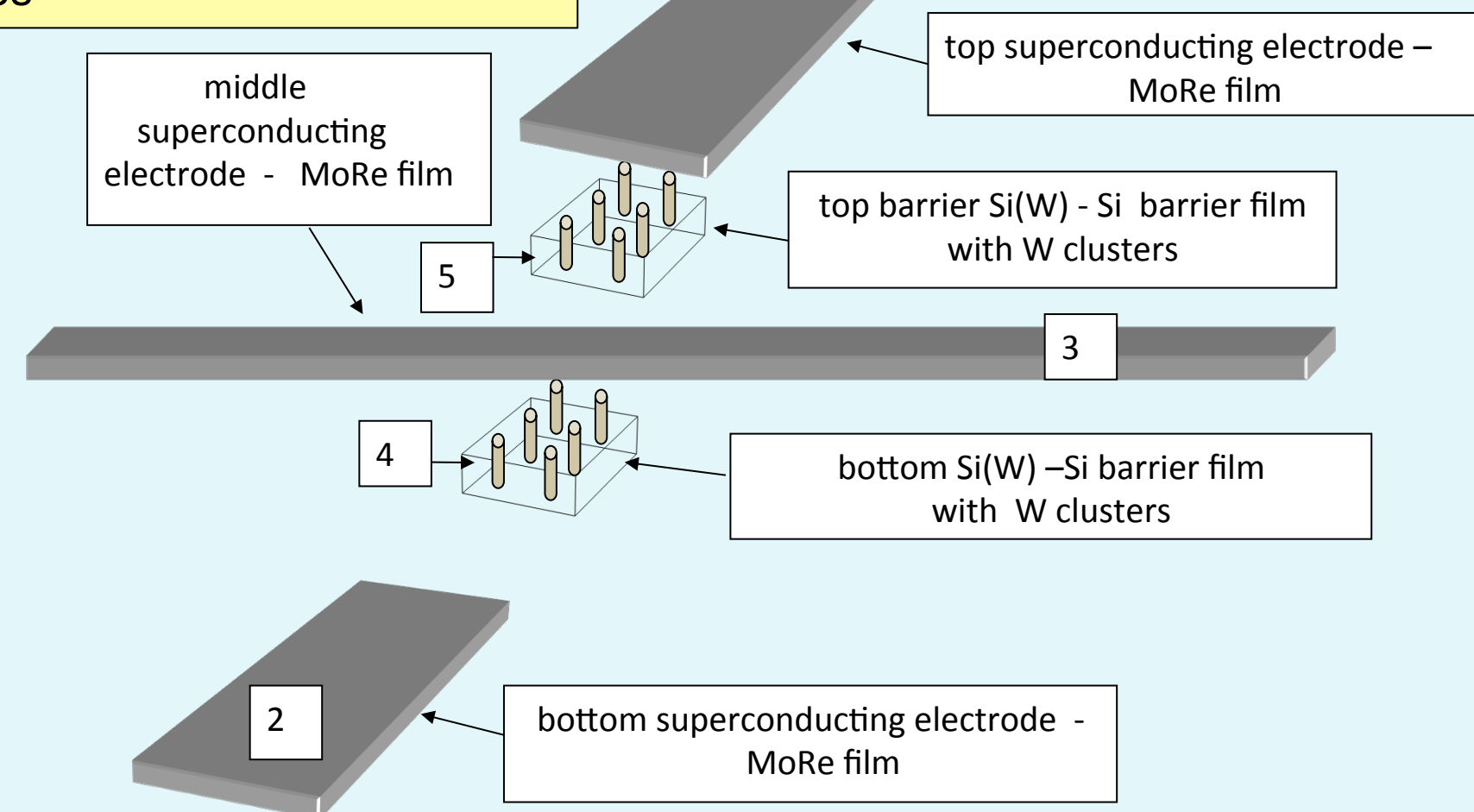
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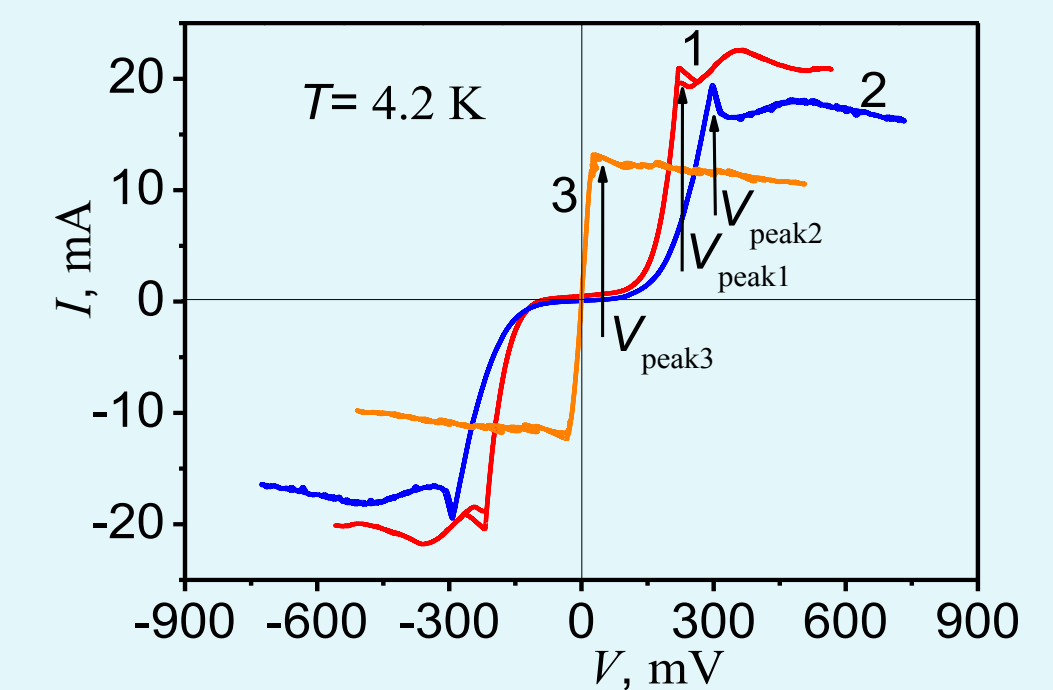
## Samples



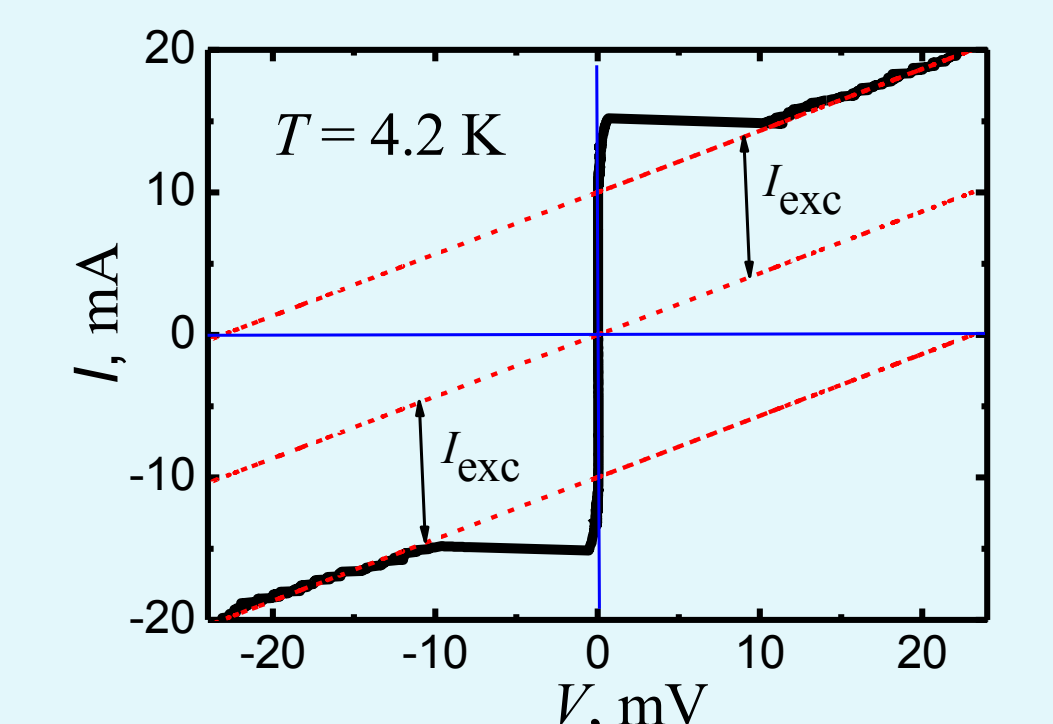
combined magnetron target – single crystal Si wafer with W wires



schematic view of the fabricated four-terminal heterostructures

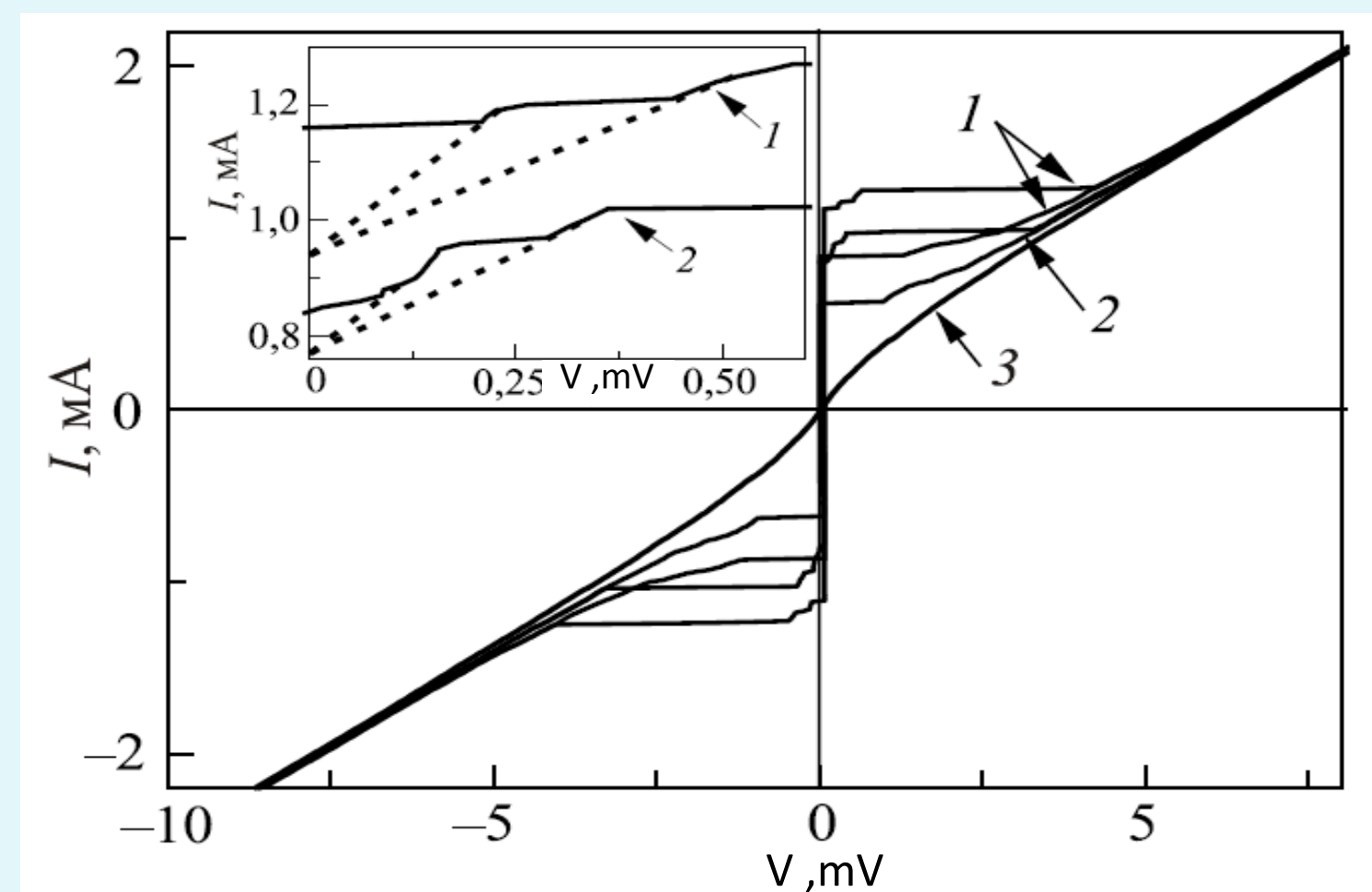


Current-voltage characteristics of MoRe/SiO<sub>x</sub>(W)/MoRe samples at various W contents in a silicon-oxide barrier with the thickness  $d$ : 1 -  $d = 15$  nm,  $n_W \approx 4$  at. %; 2 -  $d = 30$  nm,  $n_W \approx 4$  at. %; 3 -  $d = 15$  nm,  $n_W \approx 5-6$  at. %.

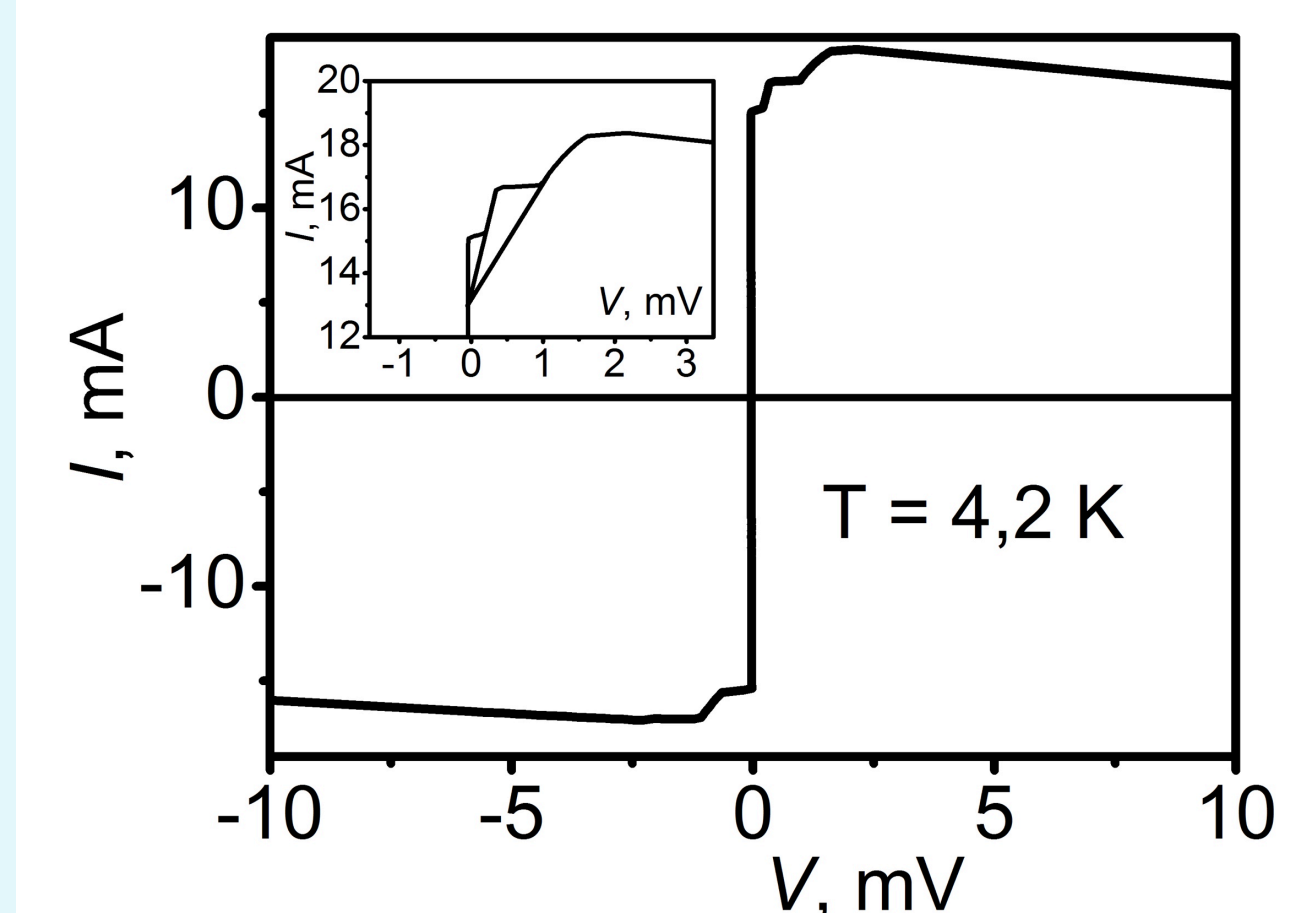


$I$ - $V$  curves of MoRe/SiO<sub>x</sub>(W)/MoRe samples with a supercurrent at W content -  $n_W \approx 8$  at. % with a barrier thickness  $d = 15$  nm.

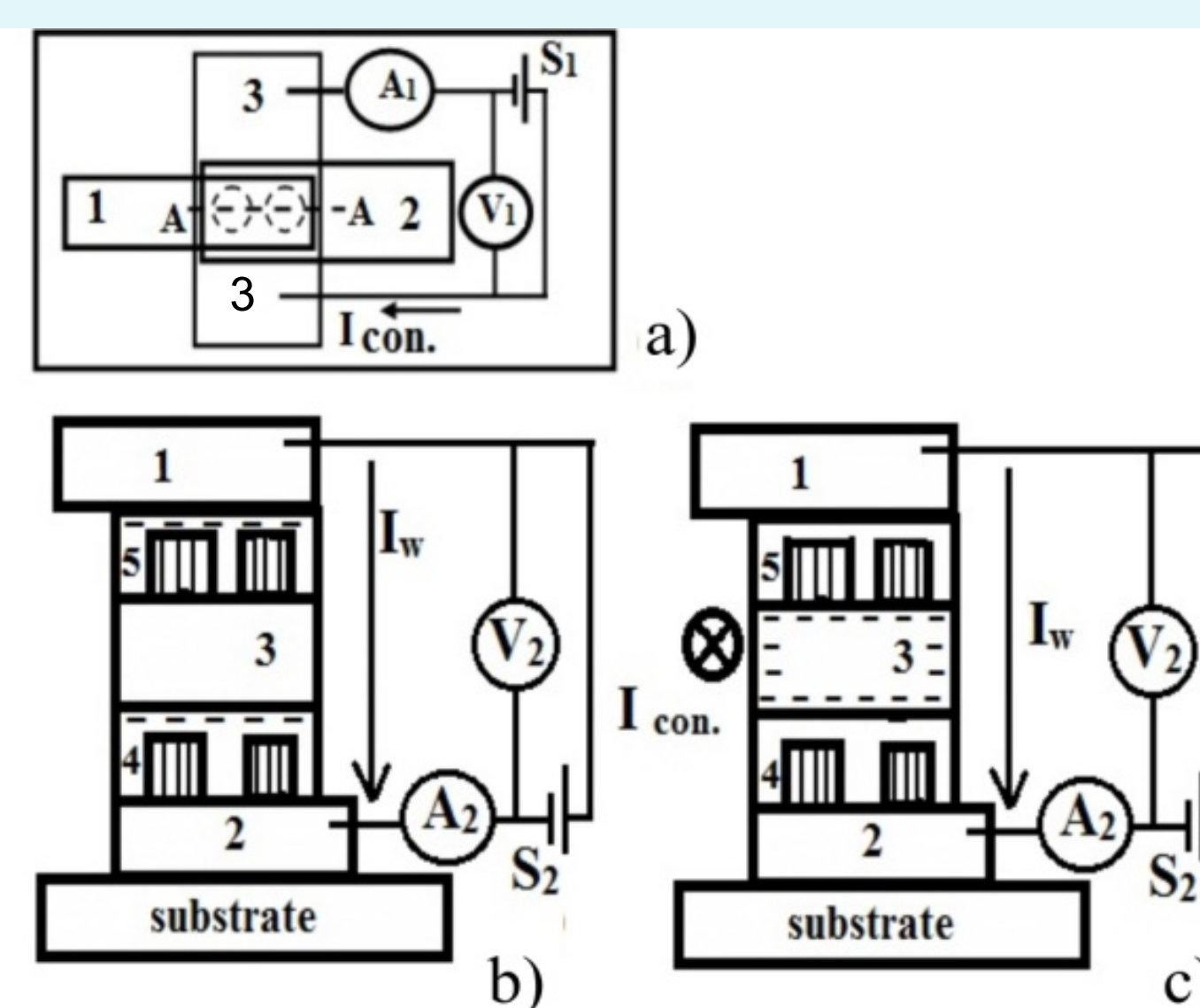
## Experimental results



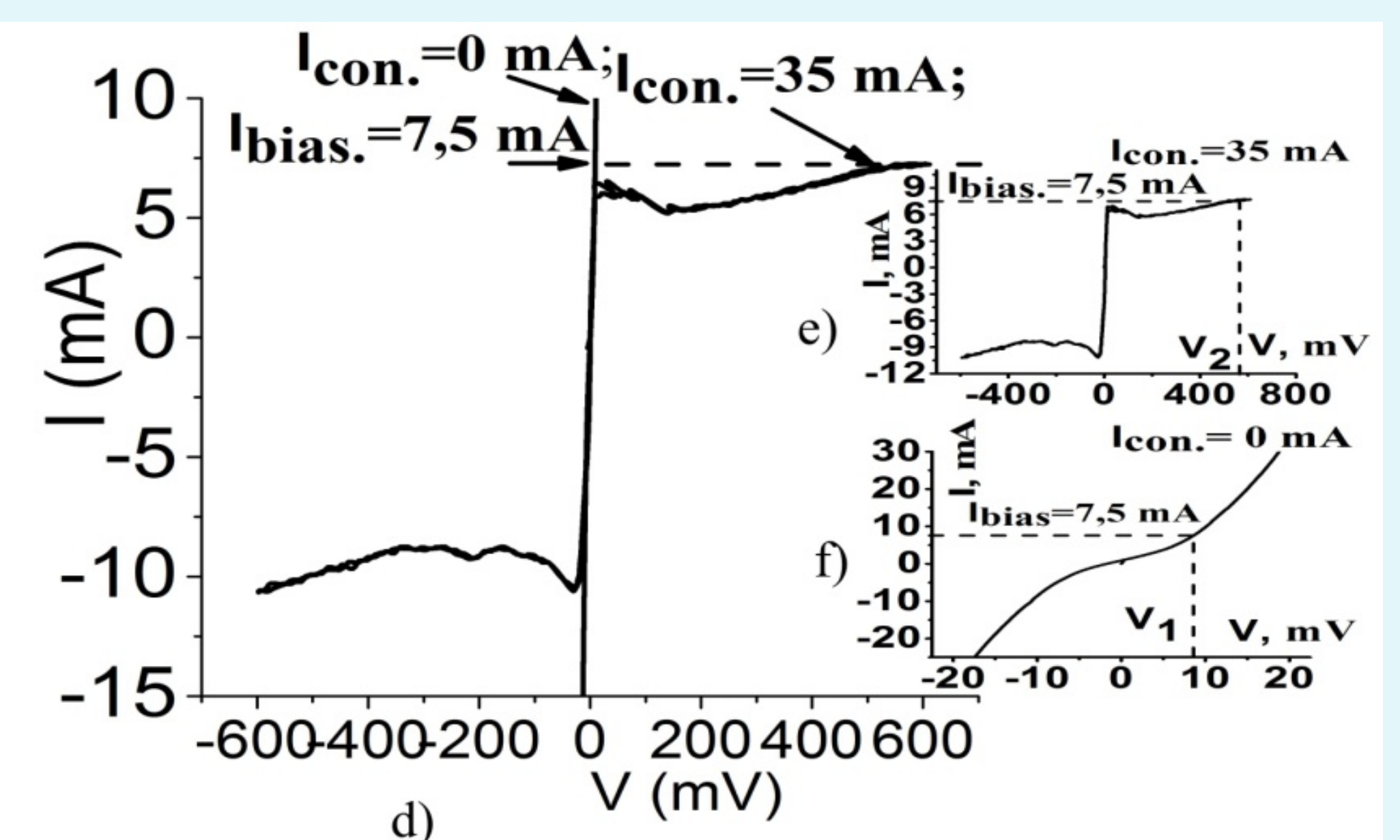
$I$ - $V$  curves of MoRe/SiO<sub>x</sub>(W)/MoRe heterostructures under microwave irradiation with  $f = 11$  GHz and at various power levels  $P_3 > P_2 > P_1$



$I$ - $V$  curve of a superconducting MoRe film with the PSCs.



(a) schematic top view (a); charge distribution (electrons are marked by "-") without control current  $I_{con}$  (b) and with current (c); (d,e,f)  $I$ - $V$  curves of the investigated heterostructures.



## Conclusions

Four-terminal hybrid superconductor - semiconductor (with quantum dots) - superconductor - semiconductor (with quantum dots) - superconductor junctions have been fabricated and their  $I$ - $V$  characteristics have been measured. The devices have exhibited a switching effect: the applied voltage value can be controlled by changing the control current value which induces the PSC appearance and, as a result, the whole  $I$ - $V$  curve of the heterostructure can be controlled. Let us emphasize that the fabricated heterostructures behave like a transistor and can demonstrate voltage and power gains.

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