THE MICROTUBULE TRANSISTOR

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Abstract

I point out the similarity between the microtubule (MT) experiment reported by Priel et al \cite{1} and the ZnO nanowire experiment of Wang et al \cite{4}. It is quite possible that MTs are similar to a piezoelectric field effect transistor (PE-FET) for which the role of the control gate electrode is played by the piezo-induced electric field across the width of the MT walls and their elastic bending features.

1 The MT transistor-like behavior

A very interesting experiment has been published recently by Priel et al \cite{1}. Isolated MTs were visualized and identified under phase contrast microscopy and connected to the tips of two patch-clamp amplifiers such that electrical stimulation could be applied to one of them, whereas the electric signal could be collected with the other one.

MTs were electrically stimulated by applying 5-10 ms input voltage pulses with amplitudes in the range of ±200 mV. The resulting electrical signals were obtained at the opposite end of an MT, 20-50 μm away, with a pipette also connected to a patch amplifier, which was kept “floating” at 0 mV.

Two remarkable findings are reported:

First, coupling of the stimulus pipette to an MT increased the overall conductance of the pipette by > 300%.

Second, the signals reaching the collection site were in about one third of the cases higher than those obtained in free solution.

Moreover, the MT amplified both the electrical pulse injected at the stimulus site and the collection site as well.

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Thus the overall conclusion is that MTs improve electrical connectivity between two locations in saline solution.

The currents measured at the collection site were linearly dependent on the stimulus pipette input voltage, indicating a strictly inverse ohmic response, i.e., linear amplification. The MT conductances reached up to 9 nS, much higher than that expected from channel conductances (5-200 pS).

The authors claim that their findings demonstrate that electrical amplification by MTs is equivalent to the polymer’s ability to act as a biomolecular transistor. In a minimalistic way, both a constant electrical polarization and an active component are required.

This experiment supports previous molecular dynamics simulation of tubulin structure [2, 3] indicating a strong negative surface charge distribution of the order of 20 electrons per monomer, distributed more on the outer surface than in the inner core with ratio of $\sim 2:1$. They also point to a constant (permanent) electric polarization, which follows localized Nernst potentials arising from asymmetries in the ionic distributions between the intra- and extra-MT environments. This polarization is modulated by electrical stimulation such that the forward-reverse biased junctions of an intramolecular transistor creates a proper MT-adjacent ionic cloud environment, which allows amplification of of axially transferred signals. The proposed model implies that intrinsic semiconductive like properties of the structured tubulin dimers are such that an effective transistor is being formed whose gating ability to modulate localized charges may help amplify axial ionic movements.

2 Are MTs piezoelectric field effect transistors?

We notice here that the experiment of Ariel et al. is very similar to a nanotechnology experiment with a new type of FET with a zinc oxide nanowire between two electrodes [4]. The electric field created by piezoelectricity across the bent nanowire serves as the gate for controlling the electric current flowing through the nanowire, thus it can be tuned on/off by applying a mechanical force.

The experimental setup consists of a 370 nm wide, 100 $\mu$m long zinc oxide nanowire across a tungsten needle tip and a silicon substrate covered with silver paint.

In order to test the response of the nanowire to mechanical stress, sequential measurements were made in which the two electrodes were approached to each other, causing the nanowire to bend. The symmetry of the $I-V$ curves
indicated good ohmic contacts. The current was found to drop significantly with the increase of bending, indicating the decreased conductance with the increased strain. When a semiconductor crystal is under strain, the change in electrical conductance is referred to as the piezoresistance effect, which is usually caused by a change in band gap width as a result of strained lattice. Some models have been proposed for homogeneous cases, however the bending of a nanowire is by no means homogeneous. Instead, the sample is bent so that the inner arc surface of the nanowire is compressed (\( \epsilon = \delta l/l < 0 \)), and the outer arc surface is stretched (\( \epsilon > 0 \)), and the area close to the center of the nanowire is strain free. Therefore, the total piezoresistance of the nanowire can be obtained by an integration across the nanowire cross section and its length of the usual piezoresistance effect given by

\[
\frac{\delta \rho}{\rho} = \pi \epsilon ,
\]

where \( \rho \) is the resistance, \( l \) is the original length, and \( \pi \) is the piezoresistance coefficient.

It is not trivial to explain the observed increased resistance of the ZnO nanowire after bending. Wang and collaborators proposed the following explanation. When the piezopotential appears across the bent nanowire, some free electrons in the \( n \)-type ZnO nanowire may be trapped at the positive side surface (outer arc surface) and become non-movable charges, thus lowering the effective carrier density in the nanowire. On the other hand, the negative potential remains unchanged. Hence, the piezo-induced electric field is retained across the width of the nanowire. The free electrons will be repulsed away by the negative potential and leave a charge depletion zone around the compressed side. Consequently, the width of the conducting channel in the nanowire becomes smaller and smaller while the depletion region becomes larger and larger with the increase of the nanowire bending. An almost linear relationship between the bending curvature and the conductance was found at small bending regions. The authors have derived the following relationship for a transverse force and the bending shape of the nanowire:

\[
F_y = \frac{3YI}{L^3} y_m ,
\]

where \( F_y \) is the transverse force, \( Y \) is the Young modulus, \( I \) is the momentum of inertia, \( L \) is the total length, and \( y_m \) is the maximum bending deflection of the nanowire (usually measured with scanning electron microscopy techniques). From this, the authors have concluded that for this particular
nanowire the decrease of the conductance was quasi-linear for up to 17 nN, at which the tendency of the conductance was reduced.

3 Conclusion

The similarity between the two experiments can be employed to settle a more definite transistor model for the reported amplifying electric properties of microtubules and even for thinking of using them in future biological force sensing devices at the single or bundle level.

References

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