Demonstration of Quantum Tunneling Effect of Electrons

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When two conductors are brought till very close, the gap between them forms a potential barrier. If a bias voltage is applied but it isn't high enough to let electrons pass through the barrier, the electrons classically shouldn't be able to move through. However, in quantum mechanics, the electrons actually have a possibility to pass through the barrier. This phenomenon is called tunneling effect, and the current which passes through the barrier is so-called tunneling current. Our aim is to find out the relation between the tunneling current and the thickness of the gap. Nevertheless, since tunneling current is more easy to be observed in nano-scaled thin gap, we have to bring them close enough. By the aid of piezoelectric material and principle of lever, we does reduce the gap to nano-scaled thinness. After the experiment, we find that the tunneling current increases from 0.5 nA to 50 nA while the length of gap decreases within 10 nm from the sample. All in all, the tunneling current can only be observed in nano-scaled and it drops exponentially with the distance between two conductors.

Introduction

In quantum mechanics, an object has an opportunity to pass through a barrier which has higher energy. It is because when we solve Schrödinger equation, we find that the probability density of finding electrons is nonzero (Fig.1). In our experiment, the tunneling effect is measured and we expect tunneling current decays exponentially while the tip-sample distance increases (Fig.2).

$$I = CVe^{-2Kz}, K = \frac{\sqrt{2m\Delta E}}{\hbar}$$

Where m is the particles mass, and ΔE is the energy difference between the barrier and the particles, z is the tip-sample distance, V is the bias voltage between tip-sample, and $\hbar$ is Planck constant, C is a constant. Moreover, the tunneling current is so sensitive to atomic scale distance and so the tunneling effect is using for instrument for imaging surfaces at the atomic level, is called Scanning Tunnelling Microscopy (STM). It was first developed in 1981 by Gerd Binnig and Heinrich Rohrer and they both acquired the Nobel Prize in Physics in 1986.

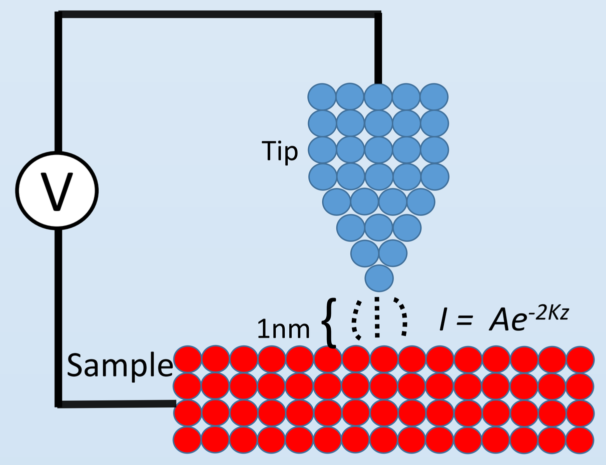


Fig.1 [1] The current has a possibility to pass through even if the tip doesn't contact with the sample.

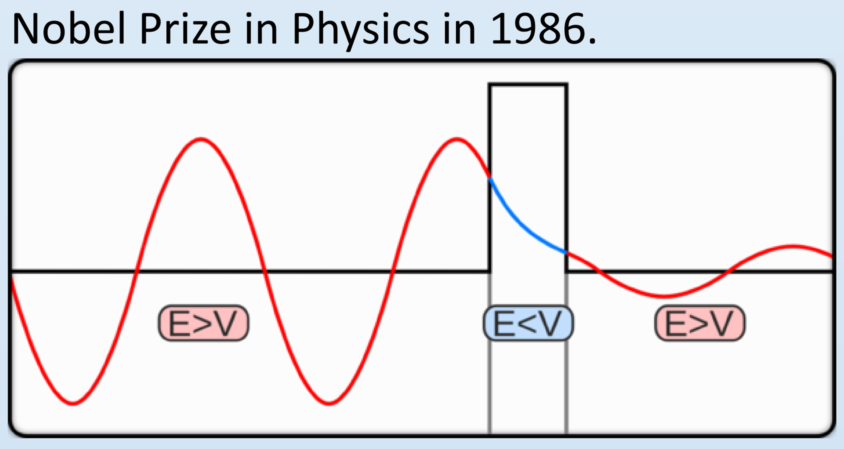


Fig.2 [2] In Schrödinger equation, $-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\varphi + V(x)\varphi = E\varphi$. The solution in the middle area is, $\varphi = Ae^{-Kz}$. Therefore we inference the tunneling current is in an exponential relation with thickness of the potential barrier.

Piezoelectricity

Piezo ceramic is a voltage-controlled material, which deforms or expands when voltage is applied. Its expansion is linearly proportional to the potential difference between it (Fig.3). We use it to bring the tip-sample distance closer. However, since the expansion is too microcosmic to observe, we use Michelson interferometer (Fig.4) to measure its expansion coefficient (Fig.5).

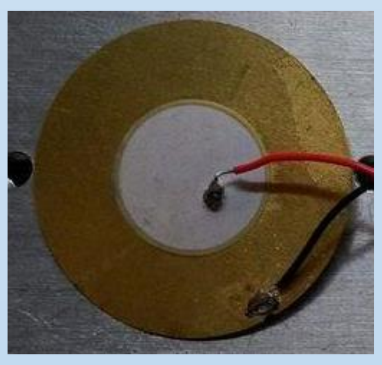


Fig.3 A 5cm diameter piezo ceramic which expands when there is voltage across it

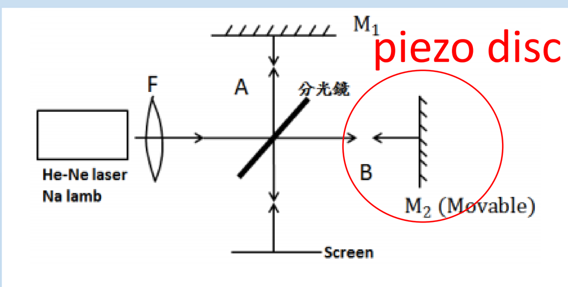


Fig.4 Michelson interferometer consists of two reflected beam of light to form constructive interference (one of the beam was reflect on the expanding piezo).

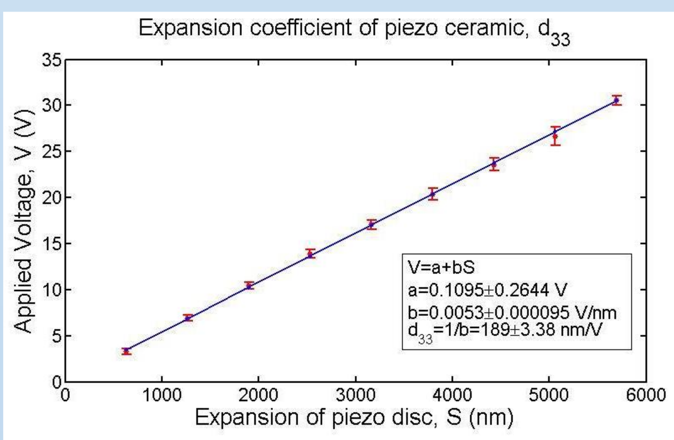


Fig.5 Expansion coefficient , d_{33}, of the piezo we measured experimentally. Which is d_{33}=189 nm/V

Current amplifier

Since the tunneling current is approximately to nA, it can't be measured directly. As a result, a current amplifier is necessary to our setup (Fig.6), which converts current to voltage by an order of 8.

$$V_{out} = I_{in} \cdot 10^8$$

Moreover, the input bias current needs to be significantly lower than the tunneling current, or the measurement will be horribly inaccurate. OPA124 is a good choice for us as it has low input bias currents around 1 pA.

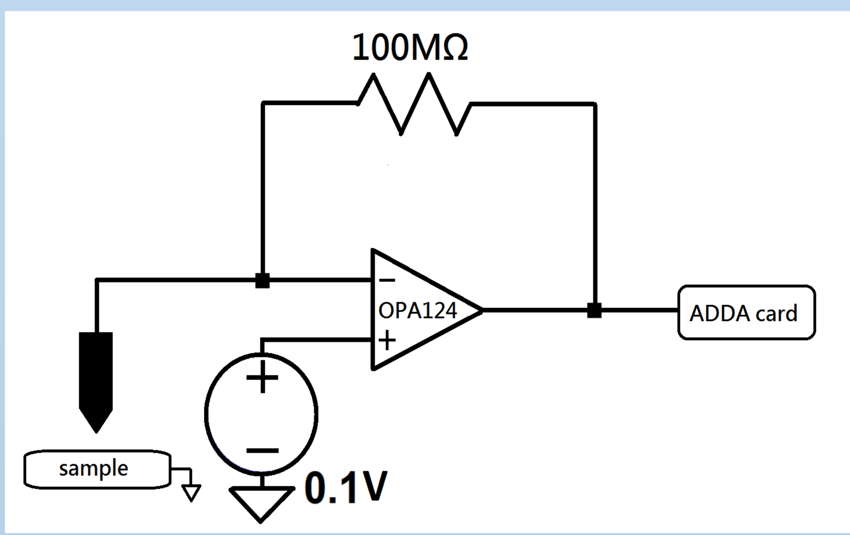


Fig.6 The bias voltage on the non-inverting terminal gives the potential difference between the tip and the sample.

Tip production

The resolution of the tunneling current depends on the thickness of needle tip, so it is necessary to make a needle with micro-scaled thickness at the top. The tip is made by etching caused by the redox reaction, and the edge of the needle is etched inward until the rest of needle drops because of gravity (Fig.7).

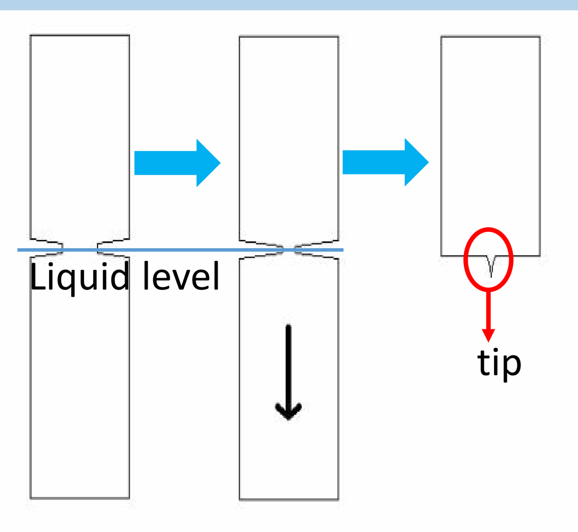


Fig.7 In reaction, the tungsten atoms are oxidized into tungsten ions.

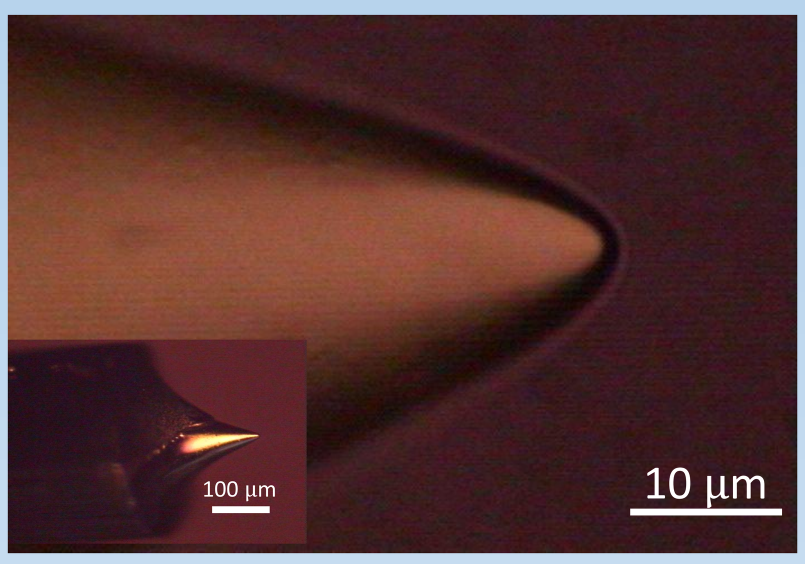


Fig.8 The width of the tip is about 2 µm.

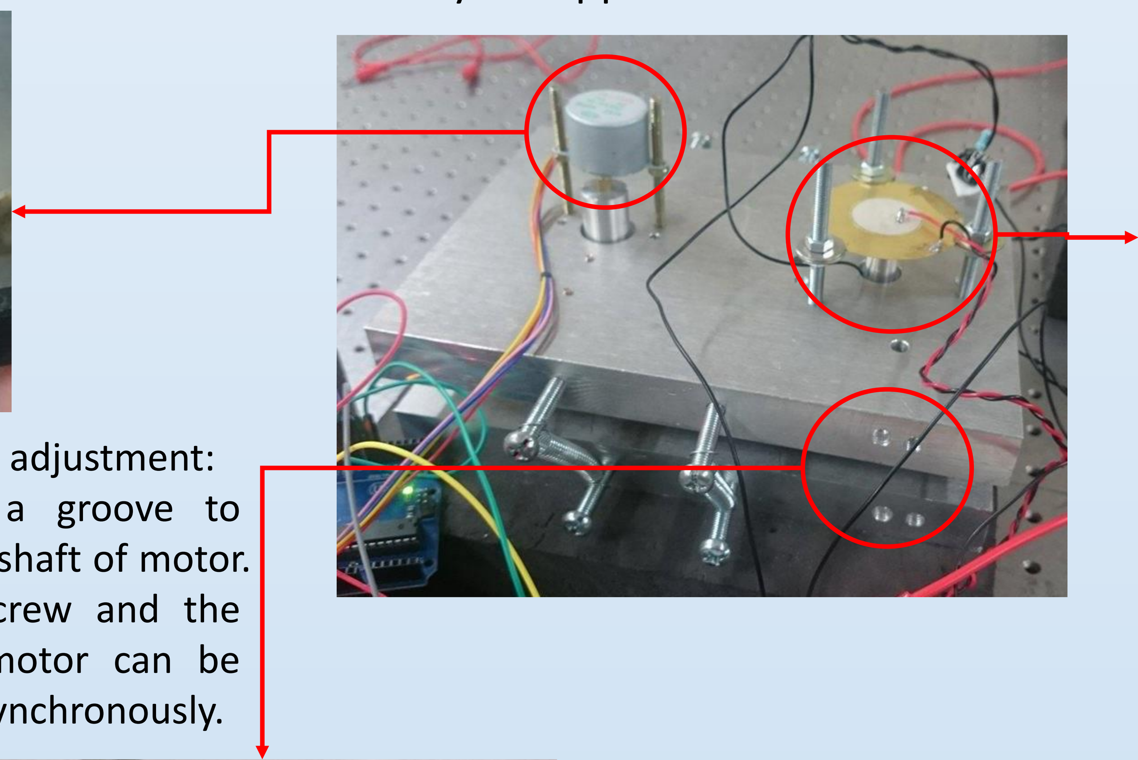
Acknowledgement

Thank for professor Cheng-Hsun Nien (粘正勳) helps us making the tips.

Experimental setup

Our purpose is making tip and sample close enough and controlling the tip moves forward to the sample stably. In our setup, the tip is fixed on the piezo ceramic (Fig.10) which is fixed on the screw (M5) by nuts. The position of the fixed point is adjustable, so it is the coarse adjustment. On the other hand, there is a fine screw on the left side of device, with the right side of fulcrum, the tip declines with the rotation of the screw in proportion, so it is our fine adjustment (Fig.9). The limitation of expansion of piezo ceramic is 1.89 µm under 10 V bias voltage, so the single step of fine adjustment should be smaller than it, or the tip will hit the sample without detection. As a result, we choose the single step is 1.58 µm when the screw rotate 22.5° which is controlled by a stepper motor.

Fig.9 Fine adjustment: We use a groove to stuck the shaft of motor. So the screw and the stepper motor can be rotating synchronously.



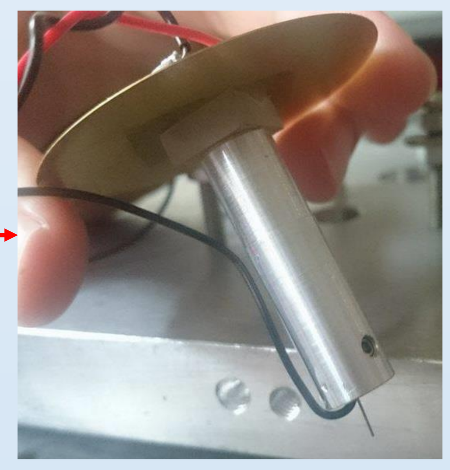


Fig.10 Since both piezo and tip have its own voltage, we need an insulator to isolate them, and we use acrylic to do it.

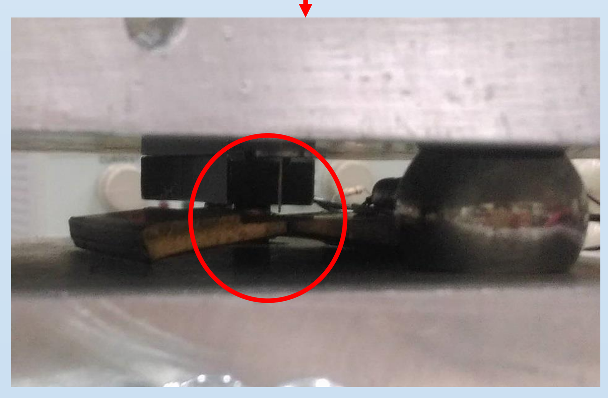


Fig.11 There are two fulcrums in the system, one is a metal ball, and the other is a fine screw, which can keep the device in horizontal line. The circle shows the location of the tip.

Experimental Result

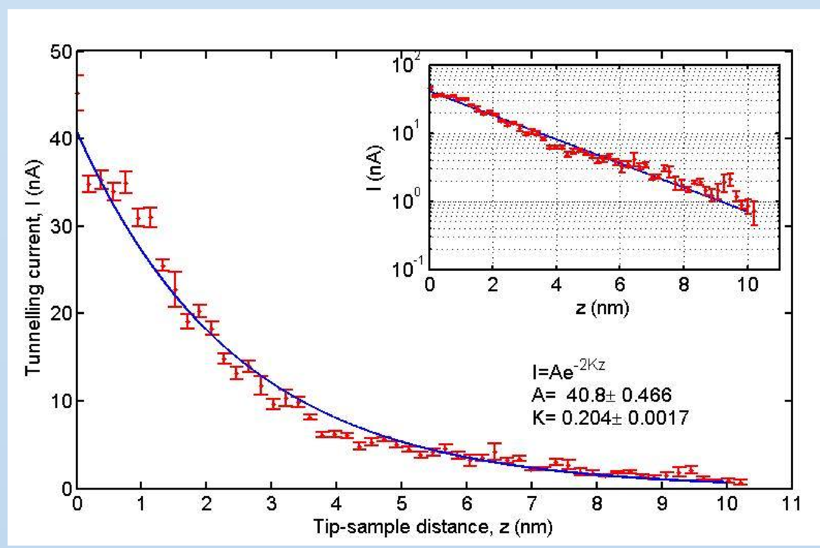


Fig.12 The graph of tunneling current against tip-sample displacement

We expect our model is exponentially decay, so we first take natural logarithm to the tunneling current and then do linear fitting. The inset was the logarithmic scale of the data. The fitting result was then taking exponential an we get $I = Ae^{-2Kz}$,while $A = 40.8 \pm 0.466$ nA and $K = 0.204 \pm 0.0017$ nm^{-1}.

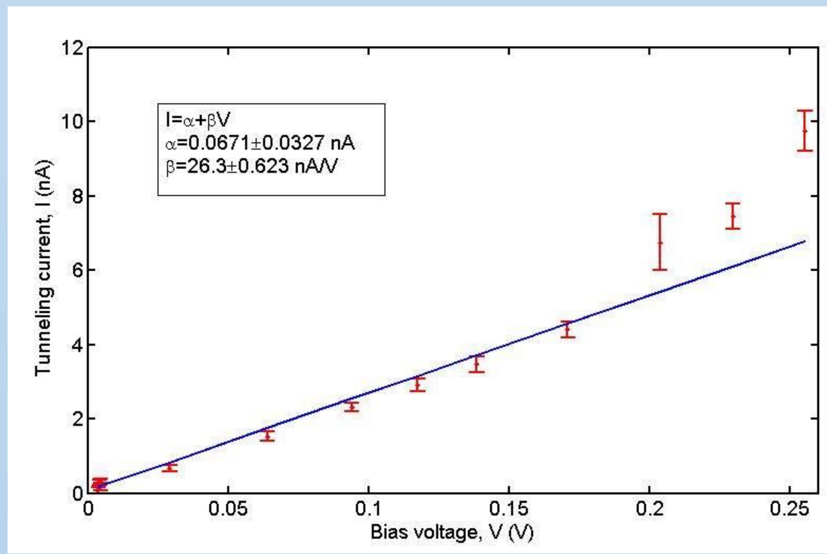


Fig.13 The graph of tunneling current against bias voltage in fixed distance

The tunneling current is $I = Ae^{-2Kz}$, $A = CV$, where V is the bias voltage and C is a constant, so we expect our tunneling current is proportional to the bias voltage, the data is taken to linear fitting. The fitting result is $I = \alpha + \beta V$,while $\alpha = 0.067 \pm 0.0327$ nA and $\beta = 26.3 \pm 0.0623$ nA $\cdot$ V^{-1}

Discussion

1. From Fig.12, we find that the tunneling current does decay exponentially while the tip-sample distance increases. Moreover, from the inset in Fig.12, we can see that the tunneling current varies from about 50 nA to 0.5 nA, almost a 100 times variation but the distance only increases for 10 nm. This gives us why the gap need to be thin enough.
2. Since the feedback resistor of current amplifier is 10^8 Ω, the range of input current should be from 0.1 nA to 50 nA and the corresponding output voltage is from 10 mV to 5V.
3. From (1.), the tunneling current increases exponentially in the distance range of 10nm, but from other reference, the typical distance range is within 1nm. However, this part remains still under exploration.
4. From Fig.13, the tunneling current with the higher bias voltage diverges from the line, we guess it is caused by the mechanical vibration.

Conclusion

1. We measure the expansion coefficient of piezo and make good use of the lever principle to control the tip-sample distance.
2. We build a current amplifier so that the tunneling current is observable.

To sum up, we combine these elements and measure the tunneling current decays exponentially almost until hundredth but the distance only increases for 10nm. Moreover, we confirm that the tunneling current is proportional to the bias voltage.

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