Yuheng Zhang Effect: Strain-Induced Electric Effect in Metals

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As is known, the piezoelectric effect and electrostrictive effect exist in some ceramics and dielectric materials. However, such effect has never been discovered in conventional metals before. Here, strain-induced electric effect in conventional metals, named after Professor Yuheng Zhang, was first uncovered theoretically in this work. This effect gives several interesting and surprising predictions for metals as follows: 1) conduction electrons in metals no longer obey Einstein diffusion relation but satisfy a new relation given in this work; 2) a metal with strain gradients at a uniform temperature is no longer an equal-electric potential body even without any external electromagnetic disturbances; 3) a metal possessing non-uniform strains may behave as an ideal p-n junction, blocking electric current completely if the applied reverse-biased voltage is not large enough; 4) the long-standing physical puzzle for thermoelectric effect of metals, the positive sign of Seebeck coefficient for metals, is unraveled by means of Yuaheng Zhang coefficient, a newly found vital coefficient induced by both thermal expansion and Yuheng Zhang effect; 5) a notable electric voltage maintains across the shock wave front in metals; 6) an electric voltage appears between two phases when phase transition happens for metals, offering a new probe to detect phase transitions. In all, this effect may expand one's fundamental knowledge on metals and find applications in various fields.

Upon application of an external stimulus, such as an applied stress, a voltage and so on, materials can exhibit interesting physical properties. The piezoelectric effect in some ceramics without center-inversion symmetry, electrostrictive effect in dielectric materials are the well-known examples. However, such effects have never been found in conventional metals [1] because of ultrahigh electric conductivity and highly efficient electric screening. The metal-based devices also have not been reported so far. It is therefore of interest to explore whether there exist similar important effects in metals or not.

In this work, it is first proposed that strains can induce an internal electric effect in metals. Upon compressive strain, volume of metal will shrink and the free electron density will increase. According to the free electron gas model, the Fermi energy increases unless the effective mass of conduction electrons increases dramatically. Like water flowing from the higher to the lower, conduction electrons from the higher-Fermi surface region will diffuse into lower-Fermi surface region. So the net positive charges and net negative charges accumulate at the higher-Fermi surface region and lower-Fermi surface region, respectively, therefore resulting in space-charge separation as shown in Figure 1. In other words, the metals possessing non-uniform strains are no longer an equal-electric potential body. For elongation strains, the principle is also applicable. So, in analogy with thermoelectric effect, an electric field will be caused and the whole processes can be described according to Fick's first law

$$\vec{J} = \sigma\vec{E} - qD\nabla n_e(\vec{r}) \tag{1}$$

where $\vec{J}$ is the net current, σ is the electric conductivity of metals, $\vec{E}$ is electric field, D is the conduction electron diffusion coefficient in metals, $n_e(\vec{r})$ is the position dependence of conduction electron density and q denotes electron charge. The first term and the second term on the right are drift current and diffusion current, respectively. Once the electrical equilibrium is reached, the net current vanishes, *i.e.*, $\vec{J}=0$ and the electric field is given by

$$\vec{E}=\frac{qD}{\sigma}\nabla n_e(\vec{r}) \quad (2)$$

On the hand, it may follow

$$\nabla E_F(\vec{r})=q\vec{E} \quad (3)$$

where $E_F(\vec{r})$ is position dependence of Fermi energy in deformed metals and this is the key relation. Based on Equation (2) and (3), one can estimate the number of transferred electrons. As shown in Figure 1, take 1 cm^3 copper with compressive strain 10 % for example, and assume the bridge width between the compressed and uncompressed zone to be 1 *um*, so the yielded electric field $E \approx 5\times10^5$ *V/m*. According to Gauss theory, the transferred electrons may be much smaller than the number of conduction electrons 10^{22}-$10^{23}/cm^3$ within copper and almost having no effect on Fermi energy.

Substituting Fermi energy expression $E_F=\hbar^2(3\pi)^{2/3}n_e^{2/3}/2m$ into Equation (2) and (3), where $\hbar$ is Plank constant, m is the effective mass of conduction electrons in metals. One may obtain the following important relation

$$\frac{D}{\sigma}=\frac{2E_F}{3n_e q^2} \quad (4)$$

This relation shows that for one given metal, *i.e.*, given Fermi energy and conduction electron density, the ratio between electron diffusion coefficient and electric conductivity is almost a constant. As usually done, if electric conductivity σ is written as $\sigma = n_e q\mu$, where μ is the related conduction electron mobility, we get the second relation in metals further,

$$\frac{D}{\mu} = \frac{2E_F}{3q} \tag{5}$$

Very clearly, this ratio is a constant, because Fermi energy almost does not alter at normal conditions. This new relation indicates that the conduction electrons in metals do not obey Einstein relation any more. To one's surprise, the difference between Equation (5) and Einstein relation is very large. For example, at room temperature 300 K, the electron diffusion coefficient given by Equation (5) may be several hundred times that given by Einstein relation. Of noted is that Equations (4) and (5) are consistent with the famous free electron model and can be derived from that model, which inversely verifies the rationality and existence of this effect. Here it should be emphasized that they are the natural results and physics revealed by this effect.

Substitute Equation (4) into Equation (2) and perform integral, it follows

$$qV = E_F(\vec{r}_1) - E_F(\vec{r}_2) \tag{6}$$

where V is the related electric voltage difference. According to Equation (2) and (6), once a conduction electron density difference is induced by strains in metals, an electric field and electric voltage will appear. Here formally, the strain-induced electric effect in metals is denominated Yuheng Zhang effect [2].

In addition, the famous Wiedemann-Franz law gives $\frac{\kappa}{\sigma}=\frac{\pi^2}{3}\left(\frac{k_B}{q}\right)^2 T$, where κ denotes thermal conductivity, k_B is Boltzmann constant and T is temperature. Combing Equation (4) and Wiedemann-Franz law, one may obtain

$$\frac{\kappa}{D}=\frac{\pi^2 k_B^2 n_e T}{2E_F} \tag{7}$$

Thus, the relations between the three physical variables in metals, conduction electron diffusion coefficient *D*, thermal conductivity κ and electric conductivity σ are revealed completely.

Let us examine the difference between Yuheng Zhang effect and other similar effects, *e.g.*, Galvani potential and Volta potential. They all can produce the electric voltage which depends on the related Fermi energy difference. The distinct point lies in the fact that Galvani potential happens at the interface between two different solids [3, 4] and Volta potential appears between two different metals when they contact each other and are in thermodynamic equilibrium [5], whereas Yuheng Zhang effect occurs within the same body of a metal.

Yuheng Zhang effect is compared with another important effect, piezoelectric effect. They are totally different from each other due to the following points: 1) the response materials are different: piezoelectric effect exists in ceramics without center-inversion symmetry while Yuheng Zhang effect occurs in non-uniformly deformed metals; 2) the mechanisms are different: for piezoelectric effect, compression alters the polarization whereas for Yuheng Zhang effect strains change the Fermi surface, and therefore cause the electron diffusion and electric field and voltage; 3) the response areas are different: piezoelectric effect appear in the whole area of material under stress while Yuheng Zhang effect only happens in the regions possessing non-uniform strains.

Pointed out is that Yuaheng Zhang effect and the previously obtained relations also apply for liquid metals, because theories and experiments indicate that liquid metals could also be described by free electron gas model and all the related concepts [6, 7, 8], e.g., Fermi energy, free electron density and so on.

Now, let us address the properties and applications of Yuheng Zhang effect from six aspects. First, astonishingly, it can give an ideal rectifying junction behaving as the famous p-n junction. As shown in Figure 2, for a metal with definite compression strain on the left and no strain on the right, if an external voltage V_e is applied in the way of forward bias shown in Figure 2(a), a current may flow through the whole metal. However, if the external voltage V_e is applied in the reverse bias way shown in Figure 2(b), no current flows through the metal unless the external voltage V_e surpasses the critical electric voltage V_z due to Yuheng Zhang effect, as shown in Figure 2(c). The difference between this metal junction and conventional p-n junction resides in the fact that for the reverse bias a tiny current still flows through the p-n junction, however the current is rigorously zero for this metal junction. For the reverse bias configuration, when the external applied voltage surpasses V_z, the measured resistance is larger than its intrinsic value. So when carrying out the resistance measurement of metals with non-uniform strains, one must be careful. Maybe a better method is to measure the resistance in both forward bias and reverse bias way, and then take the smaller resistance value.

Second, it also alters the I-V characteristics of normal metal-insulator-superconductor (N-I-S) and superconductor-insulator-superconductor (S-I-S) junctions as shown in Figure 3 and 4. If the normal metal or superconductor undergoes a compressive strain, the related Fermi energy is lifted, resulting in the voltage-biased I-V relationships shown in Figure 3 (b)(d) (c)(f) and Figure 4(b)(d) (c)(f). Here we neglect the strain effects on the superconducting energy gap 2Δ. It should be emphasized that if there is no intermediate insulator within these N-I-S junctions but the intermediate strain gradient region is narrow enough for electron tunneling, *e.g.*, nanometers in thickness, these voltage-biased I-V relations may also apply.

Third, it is interesting to consider obvious Yuheng Zhang effect caused by the gravity, e.g., the earth. As is known, the earth's inner core and outer core are composed mostly of iron and nickel. Owing to gravity, spherically symmetrical strains are produced along the radius of the earth and Yuheng Zhang effect appears, and therefore the negative charges and positive charges accumulate at the core-mantle boundaries and center of earth's inner core, respectively. When the body with charge separation rotate spontaneously, a magnetic field is yielded. This may enlighten people on source of the earth's magnetic field.

Fourth, let us turn to thermoelectric effect. When the temperature gradient happens in metals, not only the thermoelectric effect but also thermal expansion-induced Yuheng Zhang effect occur. According to Equation (2), magnitude of voltage caused by Yuheng Zhang effect may be described by

$$\vec{E}=\frac{1}{q}\frac{\partial E_F}{\partial T}\nabla T \tag{8}$$

$$S_Z=\frac{1}{q}\frac{\partial E_F}{\partial V}\frac{\partial V}{\partial T} \tag{9}$$

And for isotopic metals

$$S_Z=-\frac{2}{q}\alpha E_F \tag{10}$$

where α is a linear expansion parameter, T is temperature, q denotes electron charge. Here S_Z is a new coefficient caused by thermal expansion-induced Yuheng Zhang effect, which is named as Yuheng Zhang coefficient [2] in this work. Obviously, our measured Seebeck coefficient is summation of Yuheng Zhang coefficient S_Z and hot electron diffusion thermopower, denoted as S_d which was believed to be the Seebeck coefficient before,

$$S=S_Z+S_d \tag{11}$$

Based on Equation (10), S_Z is always positive for electron carriers and is proportional to the linear thermal expansion parameter. Let us examine magnitude of S_Z and S_d at room temperature, and the results are given in Table 1. As shown in this table, the electron diffusion thermopower is always negative, which agrees with the free electron gas model. Excitingly, the long-standing problem in solid state physics, the positive sign of Seebeck coefficient in some conventional metals [10], is tackled here. The measured Seebeck coefficient is summation of hot electron diffusion thermopower and Yuheng Zhang coefficient, and for some metals the positive Yuheng

Zhang coefficient exceeds the hot electron diffusion thermopower, therefore leading to positive Seebeck coefficient. Of noticed is that magnitude of hot electron diffusion thermopower is larger than expected, which might suggest the important role of phonons. On the other hand, if a metal presents negative thermal expansion under some conditions, the related Seebeck coefficient is predicted to be much larger than normal metals.

Fifth, for metals, when the phase transition occurs at some temperature and pressure, the conduction electron density is usually lifted due to volume shrinkage or expansion, causing modification of Fermi energy. Therefore, an electric voltage is expected to appear between the initial phase and transition phase. In other words, phase transition of metals is usually accompanied by an electric voltage between the two phases. The magnitude of this voltage may be equal to Fermi energy difference,

$$-q(V_1 - V_2) = E_{F1} - E_{F2} \tag{12}$$

where E_{F1} and E_{F2} are the related Fermi energy for initial phase and transition phase, V_1 and V_2 are the related electric potential, respectively. So, besides the conventional methods, *e.g.*, structure detection using X-rays, temperature detection using thermometer and so on, here measuring the voltage will offer people another new tool to determine phase transitions of metals, including solid-solid, solid-liquid and even liquid-liquid phase transitions,.

Sixth, compression waves could produce large strain differences in metals, *e.g.*, plane shock waves. So, across the shock wave front Yuheng Zhang effect emerges, causing a notable electric voltage, which may also be described by Equation (12) and give people a valid method for confirming this effect.

In the previous parts, the theory has been clarified and some applications of Yuheng Zhang effect have been discussed. The remnant problem is how we can confirm this effect. The first point is that a region with definite strain in metals should be yielded. Second, the measuring electrical circuit should be valid. In the following parts, a possible measuring method is discussed.

Plane shock waves may be a good tool to produce the definite-strain zone in metals. It could be regarded as a one-dimensional strain wave [15]. When it penetrates into materials, two regions are produced: compressed region with definite strain after shock waves and uncompressed region in front of shock waves. Between the two regions, an electric voltage appears based on Yuheng Zhang effect. Of noticed is that although the electron diffusion speed is much slower than shock wave speed, the thermodynamic equilibrium is still reached. This is because strain gradient exists within narrow shock wave front, and electrons can diffuse from more compressed areas into less compressed areas by a mean free path. The electron diffusions within shock wave front may form a continuous electron motion row like the situation of electron motions in conventional electric currents. Once electrons leave the compressed region or arrive at the uncompressed region, they quickly reach electric equilibrium state in the two zones. The time scale may be less than $10^{-15}\,s$ [16], which is short enough and guarantees thermodynamic equilibrium. Take the assumption that static dielectric parameter in the two zones is the same. Thus, the net positive charge distribution may be symmetric with the net negative charge distribution, if the initial electric voltage of original metal sample is zero. So the electric voltage between uncompressed region and zero potential, *e.g.*, the earth, might be half of the electric voltage between the two regions, and the experiment setup shown in Figure 5 may be applicable.

In summary, to the best of our knowledge, Yuheng Zhang effect, *i.e.*, strain-induced electric effect in conventional metals is first discovered in this work. This effect shows and predicts that 1) conduction electrons in metals satisfy a new relation given in this work but no longer conform to Einstein diffusion relation; 2) even without any external electromagnetic disturbances a metal with non-uniform strains at a uniform temperature is not an equal-electric potential body; 3) a metal with non-uniform strains may display rectifying effect and behave as an ideal p-n junction; 4) a newly vital coefficient caused by both thermal expansion and Yuheng Zhang effect is proposed in this work, which is successfully utilized to solve the long-standing physical puzzle for thermoelectric effect of metals, the positive sign of Seebeck coefficient for metals; 5) a notable electric voltage maintains across the shock wave front in metals; 6) across interface of two phases when phase transition happens for metals, an electric voltage emerges, offering a new probe to detect phase transitions. This effect promotes people's basic knowledge on metals and get multi-field applications in the future.

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[2] Both the effect and coefficient are named after author's mentor Prof. Yuheng Zhang at University of Science and Technology of China to express sincere appreciation for his patient and kind guidance.

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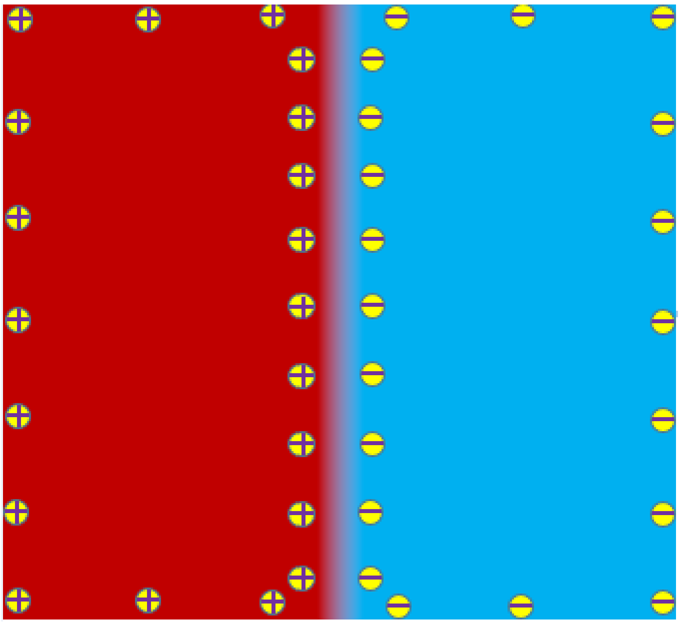

Figure 1. Schematic diagram of Yuheng Zhang effect. The red area denotes compressed metal region while the blue area is the uncompressed metal region. The yellow circled with “+” and “-” signs denote the accumulated positive charges and negative electrons, respectively. For the red region under compression, the conduction electron density increases and Fermi energy rises, so the conduction electrons diffuse into the blue region. As a result, net positive charges are left in the compressed region whereas net negative charges exist in the uncompressed metal region, causing an electric voltage between the two metal regions.

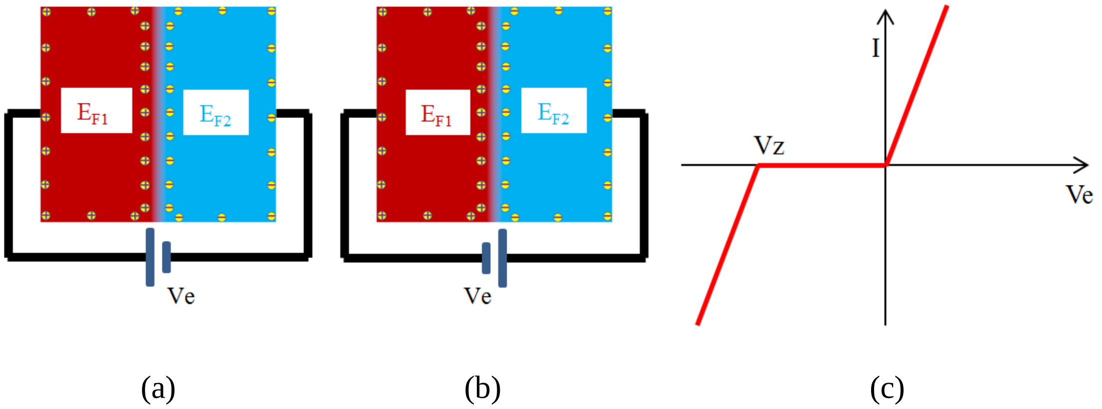

Figure 2. Schematic diagrams of electrical circuit for resistance measurement using an external applied voltage V_e. (a) Forward bias: an external positive terminal is connected with positively charged zone, *i.e.*, compressed zone; (b) Reverse bias: an external positive terminal is connected with negatively charged zone, *i.e.*, uncompressed zone; (c) current-external applied voltage (I-V) characteristics. The modified Fermi energy for the compressed zone and uncompressed zone are E_{F1} and E_{F2}, respectively. And the related Fermi energy difference $E_{F1} - E_{F2} = qV_Z$, where q is electron charge and V_Z is the voltage arising from Yuheng Zhang effect.

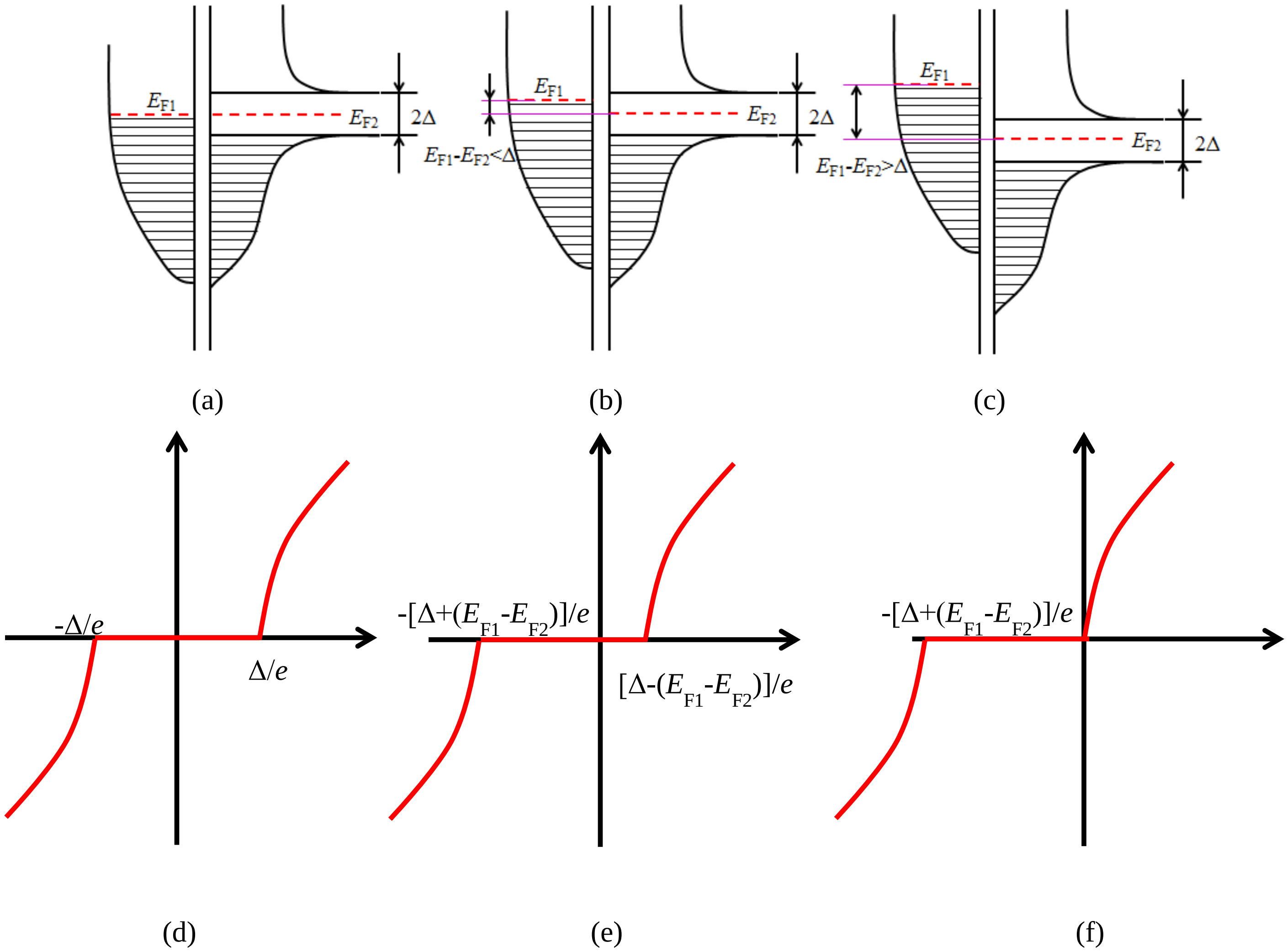

Figure 3. Schematic diagrams of typical strain-altered metal-insulator-superconductor (N-I-S) junctions and the related I-V (current- voltage) characteristics of these junctions at zero temperature. (a) the original N-I-S junction, normal metal on the left possesses Fermi energy E_{F1}, and the same Fermi energy $E_{F2}=E_{F1}$ for superconductor with the superconducting energy gap 2Δ on the right, (d) the I-V relationship for N-I-S configuration (a) under the external applied voltage and the electron charge is *e*; (b) strain-altered N-I-S junction, the metal on the left possesses the lifted Fermi energy E_{F1}, a little higher than that of superconductor $E_{F1}-E_{F2}<\Delta$, (e) the I-V relationship for N-I-S configuration (b) under the external applied voltage; (c)

strain-altered N-I-S junction, the metal on the left possesses the lifted Fermi energy E_{F1}, much higher than that of superconductor E_{F1}-E_{F2}>Δ, (f) the I-V relationship for N-I-S configuration (c) under the external applied voltage. Of emphasized is that if there is no insulator these I-V characteristic also applies, but the strain transition region between normal metal and superconductor should be narrow enough to allow electron tunneling.

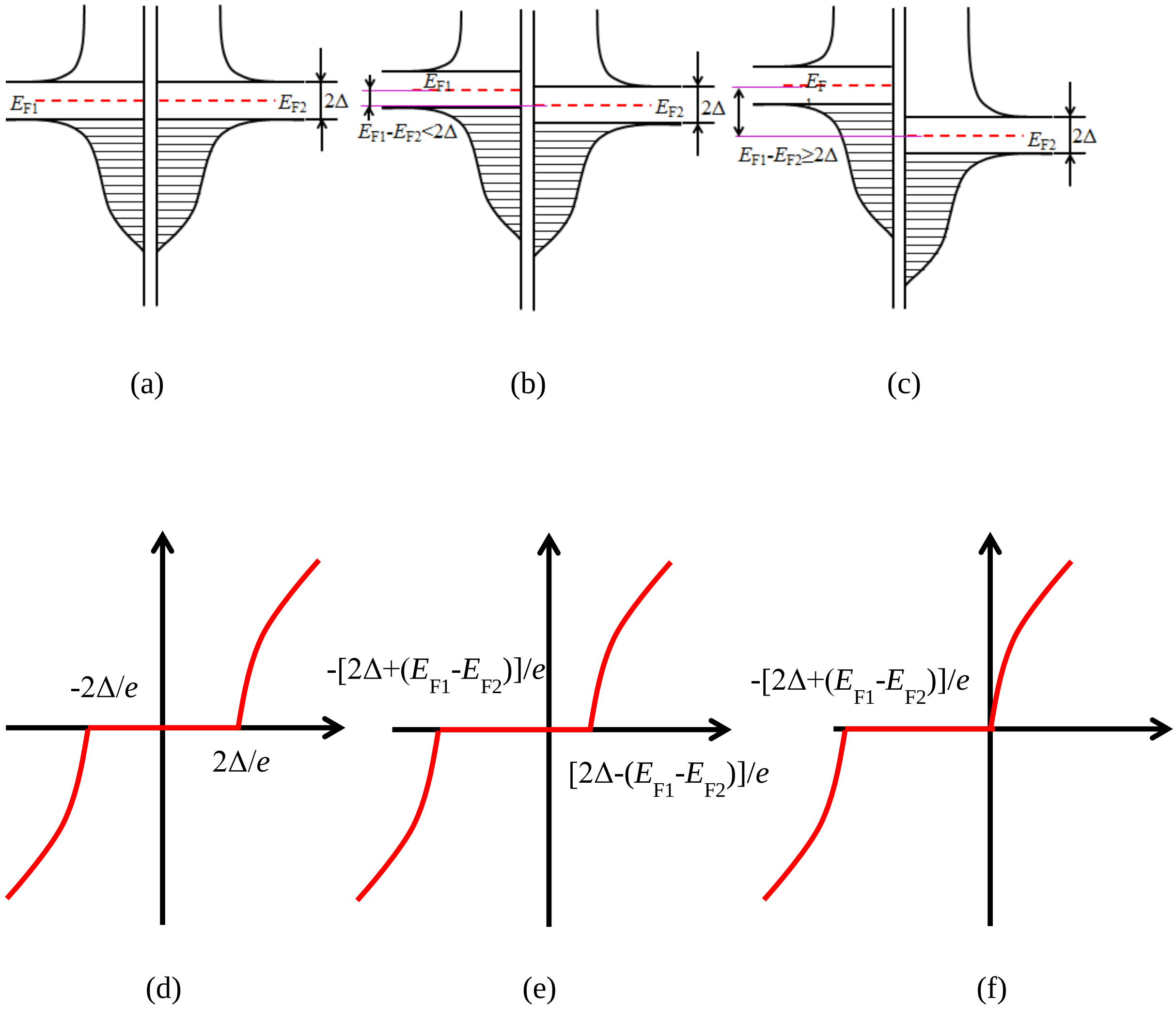

Figure 4. Schematic diagrams of typical strain-altered superconductor -insulator-superconductor (S-I-S) junctions and the related I-V (current-voltage) characteristics of these junctions at zero temperature. (a) the original S-I-S junction, the two original superconductors possess the same Fermi energy E_{F2}=E_{F1} and the same superconducting energy gap 2Δ, (d) the I-V relationship for S-I-S configuration (a) under the external applied voltage and *e* is electron charge; (b) strain-altered S-I-S junction, superconductor on the left possesses the lifted Fermi energy E_{F1}, a little higher than that of superconductor on the right E_{F1}-E_{F2}<2Δ, (e) the I-V relationship for S-I-S configuration (b) under the external applied voltage; (c) strain-altered S-I-S

junction, superconductor on the left possesses the lifted Fermi energy E_{F1}, much higher than that of superconductor E_{F1}-E_{F2}>2Δ, (f) the I-V relationship for S-I-S configuration (c) under the external applied voltage. Of noted is that if there is no insulator these I-V characteristic also applies, but the strain transition region between the two superconductors should be narrow enough to allow electron tunneling.

Table 1. Thermal expansion parameter α, Fermi energy E_F, Seebeck coefficient, Yuheng Zhang coefficient S_Z and electron diffusion thermopower S_d for metals.

Metals	E_F/eV [9, 10]	α /(10^{-6} K^{-1})[11]	S/(μVK^{-1}) [12,13,14]	S_Z/(μV K^{-1})	S_d/(μV K^{-1})
Al	11.63	23.1	-1.5	537.3	-538.8
Cu	7.00	16.5	1.5	231	-229.5
Ag	5.48	18.9	1.5	207.1	-205.6
Au	5.51	14.2	1.5	156.5	-155
Na	3.23	71	-7	458.7	-465.7
Pb	9.37	28.9	-1	541.6	-542.6
Bi	9.90	46	-77	910.8	-987.8
Cd	7.46	30.8	2.5	459.5	-457
Li	4.72	46	11	434.2	-423.2

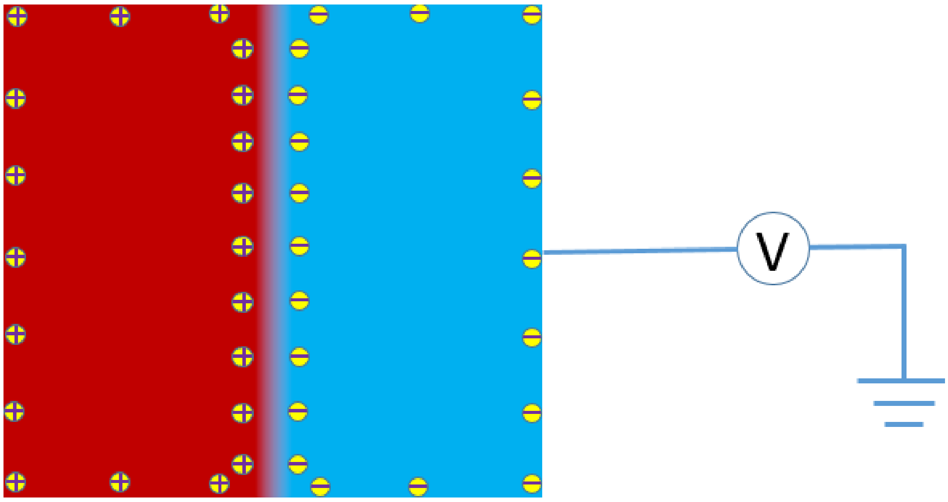

Figure 5. Designed schematic diagram of experimental setup for confirming Yuheng Zhang effect. Shock waves penetrate the metal sample from left to right. The red area denotes compressed zone after shock waves whereas the blue area is uncompressed zone in front of shock waves. The yellow circled with “+” and “-” signs denote the accumulated positive charge and negative electrons, respectively. A time-resolved voltmeter is connected with the zero potential and the blue area.