Journal of Materials Sciences and Applications
2019; 5(3): 58-62
http://www.aascit.org/journal/jmsa
ISSN: 2381-0998 (Print); ISSN: 2381-1005 (Online)

AASCIT American Association for Science and Technology

Yuheng Zhang Effect: Strain-Induced Electric Effect in Metals

Yuanjie Huang

Institute of Fluid Physics, Chinese Academy of Engineering Physics, Mianyang, China

Email address
hyj201207@163.com

Citation
Yuanjie Huang. Yuheng Zhang Effect: Strain-Induced Electric Effect in Metals. *Journal of Materials Sciences and Applications.* Vol. 5, No. 3, 2019, pp. 58-62.

Received: March 29, 2019; **Accepted**: June 30, 2019; **Published**: July 8, 2019

Abstract: As is known, the piezoelectric effect and electrostrictive effect exist in some ceramics and dielectric materials. However, such effects have never been discovered in conventional metals before. Here, strain-induced electric effect in conventional metals was first uncovered theoretically in this work. This effect may exhibit interesting properties: 1) free 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 rectify electric current and behave as a p-n junction; 4) the long-standing physical puzzle for thermoelectric effect of metals, the positive sign of Seebeck coefficient for metals is unraveled by means of both thermal expansion and this effect; 5) a notable electric field maintains across shock wave front; 6) an electrical voltage appears at interface when phase transition happens, 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.

Keywords: Mechanical-electric Coupling, Metals, Strain, Electric Properties

1. Introduction

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

2. Theoretical Methods

In this work, it is 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 surface energy alters unless the effective mass of conduction electrons increases dramatically. Like water flowing from the higher to the lower, free electrons from the higher Fermi surface region will diffuse into lower Fermi surface region. So the net positive charges accumulate at the high Fermi surface region and negative charges accumulate at low Fermi surface region, respectively, therefore resulting in space-charge separation as shown in Figure 1. In other words, a metal possessing non-uniform strains are no longer an equal-electric potential body.

An electric field will be caused and the whole processes can be described according to Ohm's law and Fick's first law [2]:

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

where $\vec{J}$ is net current, σ is electrical conductivity of metals, $\vec{E}$ is electric field, D is free electron diffusion coefficient, $n_e(\vec{r})$ is position dependence of free 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 $\vec{E} = qD\nabla n_e(\vec{r})/\sigma$. On the hand, it may follows

$$\nabla E_F\left(\vec{r}\right) = q\vec{E} \tag{2}$$

where $E_F\left(\vec{r}\right)$ is position dependence of Fermi surface energy which may be chemical potential in some literatures and this is the key relation in this work. Based on these equations, one can estimate the number of transferred electrons which almost have no effect on Fermi surface energy.

Substituting expression [3] $E_F = \hbar^2\left(3\pi\right)^{2/3} n_e^{2/3} / 2m$ into Equation (2), where $\hbar$ is Plank constant, m is effective mass of free electrons. 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 a relation in metals,

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

To one's surprise, the difference between this relation and Einstein relation is very large. For example, at room temperature 300 K, the electron diffusion coefficient given by this relation may be several hundred times that given by Einstein relation. Of noted is that it is consistent with the famous free electron model and can be derived from that model [4], which inversely verifies the rationality and existence of this effect. Here it should be emphasized that they are the natural results revealed by this effect.

According to Equation (2), if one performs integral, it can be obtained:

$$qV_z = E_F\left(\vec{r}_1\right) - E_F\left(\vec{r}_2\right) \tag{4}$$

where V_z is the related electrical voltage difference. According to Equation (2) and (4), once a free electron density difference is induced by strains in metals, an electric field and electrical voltage will appear. Here formally, the strain-induced electric effect in metals is denominated *Yuheng Zhang effect* [5].

The difference between electrical potential from this effect and other similar potentials, *e.g.*, Galvani potential and Volta potential, is examined here. They all can produce an electrical voltage due to Fermi surface energy difference. The distinct point lies in the fact that Galvani potential and Volta potential happen at the interface between two different solids [6] and metals, respectively, whereas the potential from *Yuheng Zhang effect* occurs within the identical body of a metal.

This effect is also 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 [7] while *Yuheng Zhang effect* occurs in non-uniformly deformed metals; 2) the mechanisms are different: for piezoelectric effect, mechanical stress alters the polarization whereas for *Yuheng Zhang effect* strains change the Fermi surface; 3) the response regions are different: piezoelectric effect appear in regions under stresses while *Yuheng Zhang effect* only happens in regions possessing non-uniform strains.

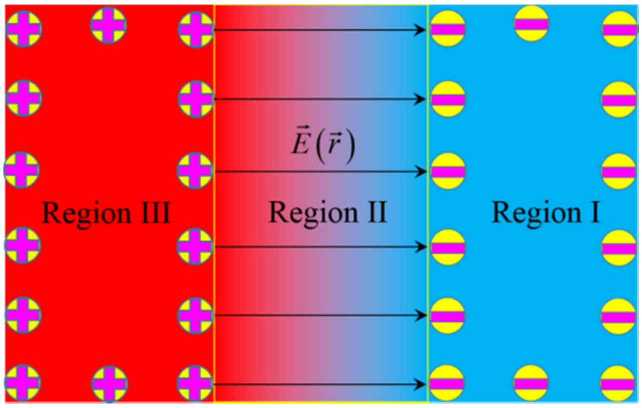

Figure 1. *Schematic diagram of Yuheng Zhang effect in a metal. The red area denotes compressed metal region while the blue area is the uncompressed region. The yellow circled with "+" and "-" signs denote the accumulated positive charges and negative electrons, respectively. For the compression region,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

Pointed out is that *Yuheng Zhang effect* and Equation (2) may also apply for liquid metals, because theories and experiments indicate that liquid metals could also be described by free electron gas model and related physical concepts [8-10] for metals, e.g., Fermi surface energy, free electron density and so on.

3. Results and Discussion

Now, properties and applications of *Yuheng Zhang effect* are addressed from six aspects. First, astonishingly, it can give birth to a rectifying junction behaving as the famous p-n junction. As shown in Figure 2, for a metal with a compression strain on the left and no strains on the right, if an external voltage V_e is applied in forward bias way shown in Figure 2 (a), a current may flow through the metal. However, if the external voltage V_e is applied in reverse bias way shown in Figure 2 (b) and the tunneling current is ignored, no current flows unless the external voltage V_e surpasses the critical electrical voltage V_z, as shown in Figure 2 (c). As for this metal junction and conventional p-n junction, actually, they are the same as each other in principle. Both of them depend on altered Fermi surface energy. One is strain altering Fermi surface energy and giving birth to an electrical voltage; the other is doping altering Fermi surface energy and thereby causing an electrical voltage. Upon the resistance measurement of metals with non-uniform strains, one must be careful because the measured resistance may be larger than its intrinsic value in the reverse bias. Maybe a better method is to measure the resistance in both forward bias and reverse bias way, and then take the smaller resistance value.

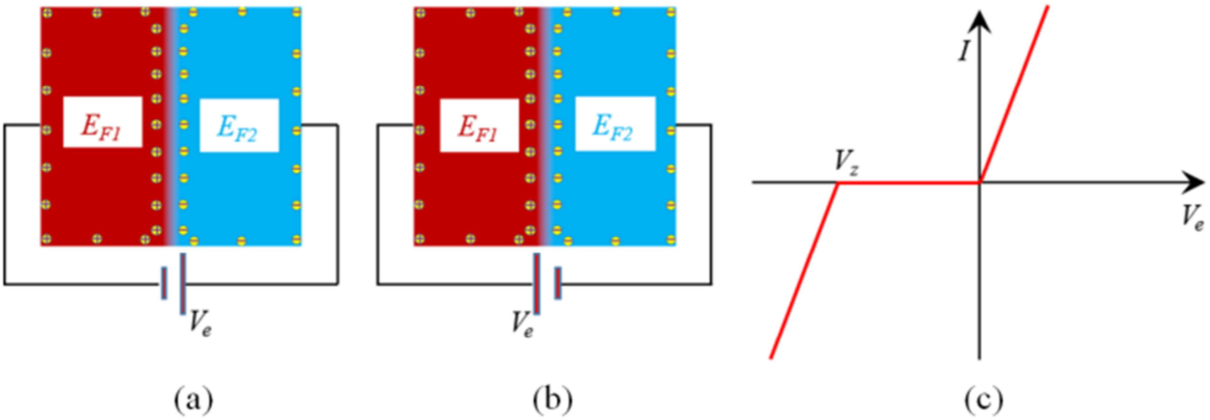

Figure 2. *Schematic diagrams of deformed metal in an electrical circuit. The modified Fermi surface energy for the compressed region and uncompressed region are E_{F1} and E_{F2}, respectively. The related Fermi surface energy difference $E_{F1} - E_{F2} = qV_Z$, where q is electron charge and V_Z is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

Second, according to reference [11], it may modify the current-voltage (I-V) characteristics of normal metal-insulator-superconductor (N-I-S) and superconductor-insulator-superconductor (S-I-S) junctions shown in Figure 3 and Figure 4. If a normal metal or superconductor undergoes a strain, its Fermi surface energy may be lifted, resulting in voltage-biased I-V relationships shown in Figure 3 (b) (e) (c) (f) and Figure 4 (b) (e) (c) (f). Here the strain effects on the superconducting energy gap 2Δ is neglected.

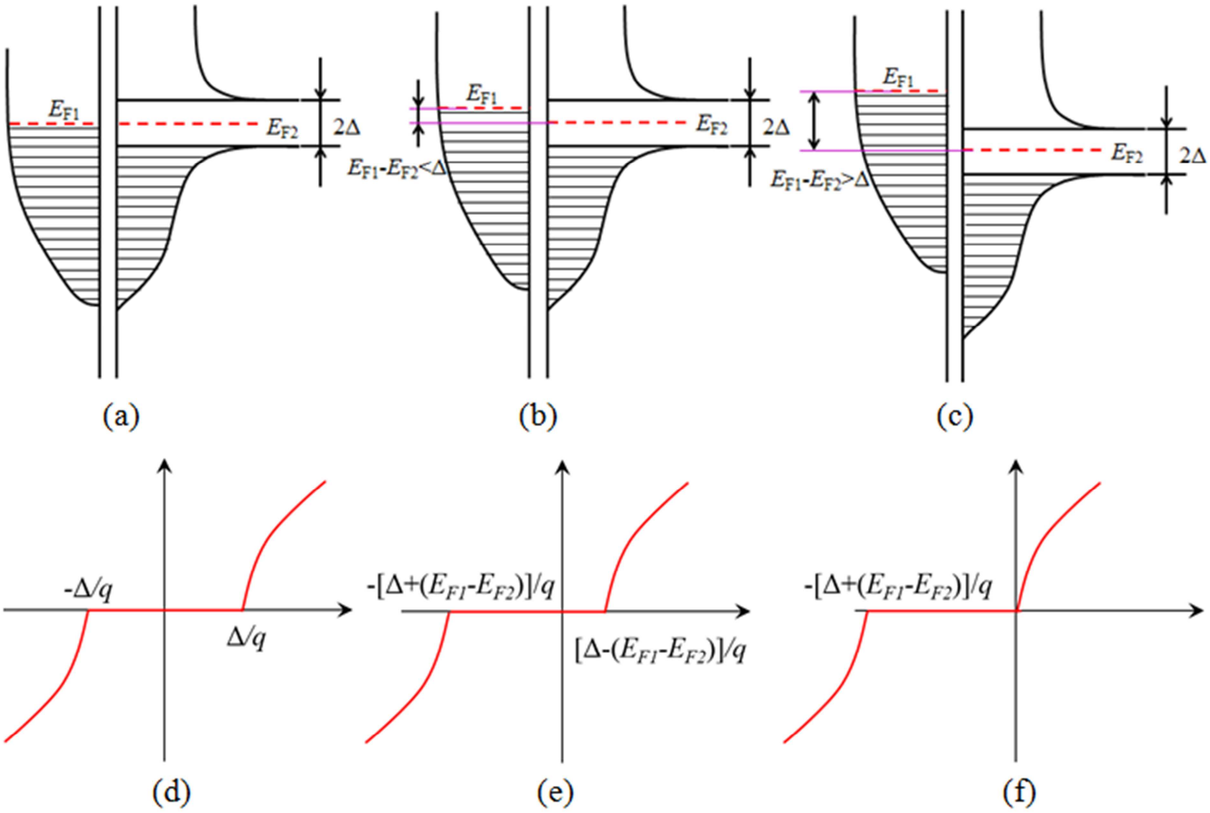

Figure 3. *Schematic diagrams of typical strain-altered metal-insulator-superconductor (N-I-S) junctions and the related I-V (current- voltage) characteristics of these junctions at zero temperature. (a) the original N-I-S junction, normal metal on the left possesses Fermi surface energy E_{F1}, and the same Fermi surface 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 q is the electron charge; (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}<Δ, (e) the I-V relationship for N-I-S configuration (b); (c) strain-altered N-I-S junction, the metal on the left possesses the lifted Fermi surface 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).*

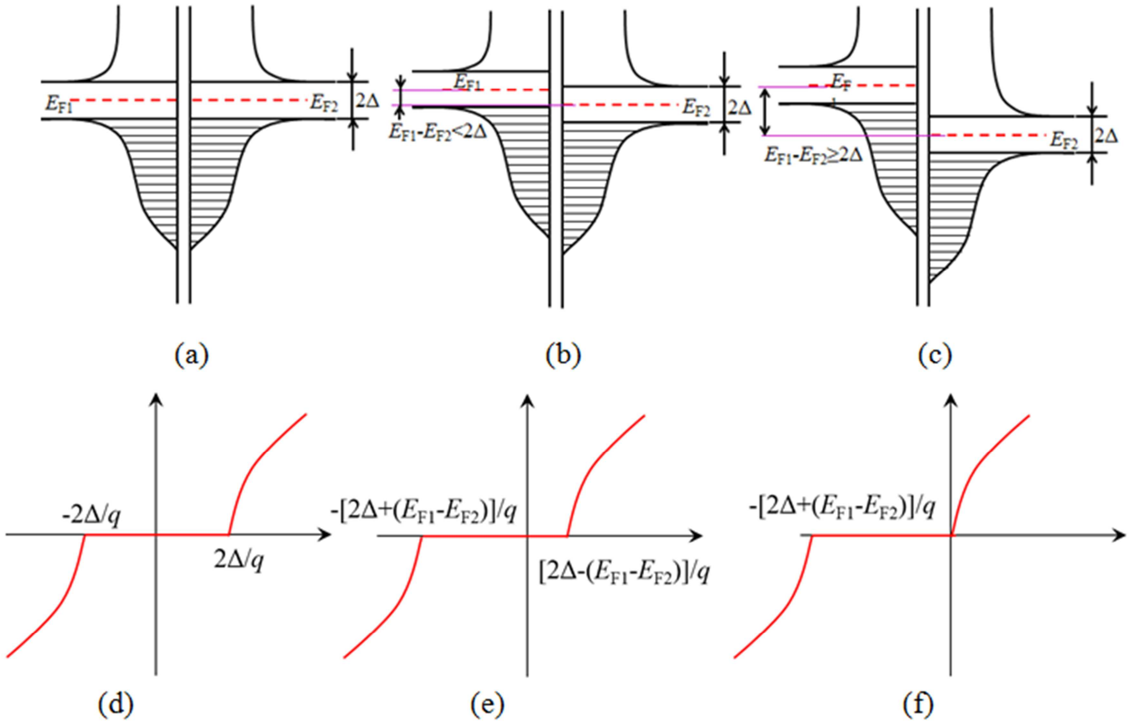

Figure 4. *Schematic diagrams of typical strain-altered superconductor -insulator-superconductor (S-I-S) junctions and the related I-V (current-voltage) characteristics of these junctions at zero temperature. (a) the original S-I-S junction, the two original superconductors possess the same Fermi surface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

Third, it is interesting to consider *Yuheng Zhang effect* caused by gravity, e.g., metal core of the earth. As is known, the earth's inner core and outer core are composed mostly of iron and nickel [12]. Owing to gravity, spherically symmetrical strains are produced along the radius and *Yuheng Zhang effect* may appear, and therefore the negative charges may accumulate at the core-mantle boundaries and positive charges at center of earth's core. When the earth's core with charge separation rotate spontaneously, a magnetic field is yielded. This may enlighten people on source of the earth's geomagnetic field.

Fourth, thermoelectric effect is turned to. According to popular definition [13-16], theoretical Seebeck coefficient may be given by $S' = \vec{E}/\nabla T$, where $\vec{E}$ is electric field and ∇T is temperature gradient. Along with temperature gradient, a concomitant strain always exist due to thermal expansion, resulting in a noticeable electric field $\nabla E_F/q$ according to *Yuheng Zhang effect*. So the measured electric field which originates from electrochemical potential difference should be $\vec{E} - \nabla E_F/q$ [17]. Therefore, relation between experimental and theoretical Seebeck coefficient may be $S = S' - \partial E_F/q\partial T - S_Z$.

$$S_Z = \frac{1}{q}\frac{\partial E_F}{\partial V}\frac{\partial V}{\partial T} \tag{5}$$

For isotopic metals, this coefficient is $S_Z = 3\alpha\partial E_F/q\partial \ln V$, where α is linear expansion parameter. S_Z is a new coefficient caused by thermal expansion and *Yuheng Zhang effect*, which is named as *Yuheng Zhang coefficient* [5].

Fifth, for metals, when the phase transition occurs at some temperature and pressure, the electron density is usually changed due to volume shrinkage or expansion, causing alteration of Fermi surface energy. Therefore, an electrical voltage is expected to appear at the interface between the initial phase and new phase. In other words, phase transition of metals may be usually accompanied by an electrical voltage. Its magnitude may be equal to Fermi surface energy difference, which may be described by Equation (4). Hence, for phase transition detection, besides the conventional methods, *e.g.*, structure detection using X-ray diffraction and so on, measuring electrical 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 field and an electrical voltage, which may also be described by Equation (4) and give people a valid method for confirming this effect.

In this work, we have clarified *Yuheng Zhang effect* and discussed some applications in theory. Some points may need experimental confirmations in the future.

5. Conclusions

In summary, to the best of our knowledge, *Yuheng Zhang effect*, *i.e.*, strain-induced electric effect in conventional metals is proposed in this work. This effect shows and predicts that: 1) a metal with non-uniform strains is not an equal-electric potential body; 2) a metal possessing non-uniform strains may display rectifying effect and behave as a p-n junction; 3) both thermal expansion and *Yuheng Zhang effect* may explain difference between experimental and theoretical Seebeck coefficient for some metals; 4) a notable electrical voltage may maintain across the shock wave front; 5) across interface of two phases upon phase transitions, an electrical voltage emerges, offering a new probe to detect phase transitions. This effect may promote people’s basic knowledge on metals and get multi-field applications in the future.

Acknowledgements

The author Yuanjie Huang is grateful for colleague Mu Li’s discussion on this topic and his valuable suggestions.

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[5] Both the effect and coefficient are named after the 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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