On the Difficulty of Energy Extraction from Built-in Voltages of Diodes and Dissimilar-Metal Junctions

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Abstract

The purpose of this brief study is to examine the energetic nature of the built-in potential difference that appears across a p-n junction of a diode, which is analogous to the contact potential difference across the terminals of a dissimilar-metal junction due to different work functions. The primary aim is to highlight the difficulty of energy extraction from such systems, and by identifying the nature of obstacles, indicate possible methods of overcoming them.

Keywords: Built-in voltage • depletion region • p-n junction • diode • contact potential difference • dissimilar-metal junction • capacitor • thermodynamics • Maxwell demon • 2LOT • second law of thermodynamics • power conversion • energy

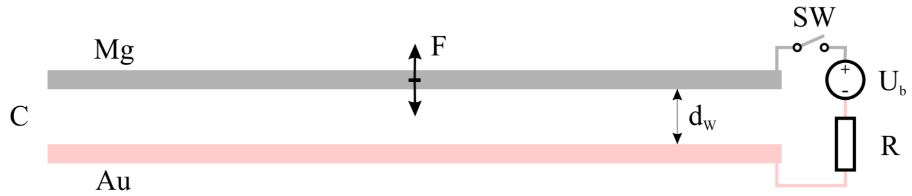

Fig. 1 Equivalent circuit representation of the parallel plate capacitor made of different metals with movable plates.

1 Introduction

When the p-n junction or the dissimilar metal contact is created, the diffusion current (or work function difference) converts some part of the ambient thermal energy into potential electric energy that is contained within the electrostatic field of the depletion region, and within the resulting E-fields present elsewhere inside- and around the device.

The ambient thermal energy conversion into electrical energy in this process can't be reasonably denied, therefore it is also undeniable that for the brief transient time period while the depletion region is established and thermal equilibrium reached, the 2nd law of thermodynamics (2LOT) is violated.

The official arguments of classical thermodynamics defending the general validity of 2LOT are based on the claims against the continuous repeatability of this process that would make the practically useful energy extraction from ambient heat possible. Although Nature generally tends to follow conservative rules that give her stability, there are natural- and also man made phenomena, where local entropies decrease, and thermal energy is converted into other forms of energies or work. Some inventions of Dr. Sheehan are claimed to be capable of violating the 2LOT, not only during the initial transient creation of a depletion region, but also continuously by repeating an energy extraction cycle [1, 2, 3, 4].

Before getting into the studies of principles that allow the circumvention of the 2LOT (in other papers) and enable special devices to convert ambient heat into other forms of energy, let's examine the associated natural obstacles, and see if we can overcome them in macroscopic systems using simple methods.

2 The Problem

Let's consider a parallel plate capacitor as schematically shown on Fig. 1. One plate of the capacitor is made of magnesium, and the other of gold. When the two plates are connected with a wire, a current starts flowing from the Au plate to the Mg plate (due to different work functions of the metals) charging the capacitor, until a contact potential difference $U_b \approx 1.56\,V$ is established [5, 6]. There have been several attempts to deny the existence of such charging process (and the resulting E field in the capacitor) by scientists with PhDs, one of which was written by Dr. D'Abramo [7]. Such false claims have been refuted in the reference paper [8] and other forum posts by the author. If the capacitance $C = \frac{\varepsilon S}{d}$ is sufficiently large, a considerable amount of electric energy $W_c = \frac{CU^2}{2}$ will be contained within the capacitor, despite the relatively low voltage.

The million dollar question is how to extract the energy stored within this "dissimilar-metal plate capacitor"? The usual methods of connecting an electric impedance to it using conductors (or semiconductors) would not work in an isothermal system, because the sum of contact potential differences along a closed circuit would yield zero net voltage; thus no current. Possible viable options for at least partially discharging the capacitor would be:

- **Decrease the Volta potential.** The contact potential difference across one of the dissimilar metal contacts in the discharge circuit could be changed by changing the local temperature, or even by changing the temperature of the whole system. One could charge the capacitor at high temperature, then cool down the whole capacitor together with the connected conductors, and partially discharge it at a lower temperature.
- **Increase the voltage of capacitor.** This can be accomplished by changing the capacitance of the capacitor. One way to do this is by moving the plates apart; another method is by inserting/removing a dielectric material between the plates.
- **Add external voltage to the circuit to disturb the net zero $\sum U_b$ balance.** This could be achieved by simply inserting an external voltage source into the discharging circuit. Alternatively, the additional voltage could be induced within the circuit by changing magnetic flux, or by moving a conductor in a magnetic field.
- **Use photoelectric-, or radioactive-, or field effect emission in vacuum or plasma.** If the photon energy is greater than the work function of the metal, then electrons can be emitted from the surface and they will get accelerated by the electric field of the capacitor. This will create a discharge current.

Unfortunately the discharging of capacitor via these methods doesn't guarantee a net energy extraction from the stored electric energy of the built-in potential difference. The quantitative analysis below will demonstrate one such energy extraction attmept, which will also show the reason for the failure to continuously convert ambient heat into other forms of energy in the junction in isothermal macroscopic systems.

3 An energy extraction attempt using a variable capacitor

Let's see if we can extract any net energy from the capacitor by cyclically changing the distance between the plates, thus changing its voltage. The capacitor can be either in vacuum, or within an insulator gas or liquid. The equivalent schematic circuit of the device as shown on Fig. 1 consists of a variable capacitor C; an ideal voltage source U_b that represents the built-in voltage (contact potential difference) of the dissimilar metal junction; a switch SW that symbolizes the closing or breaking of the circuit; and a resistor R that includes the internal resistance of the whole circuit, which will convert part of the extracted electrical energy into output heat.

The extraction cycle consists of 4 phases Fig. 2:

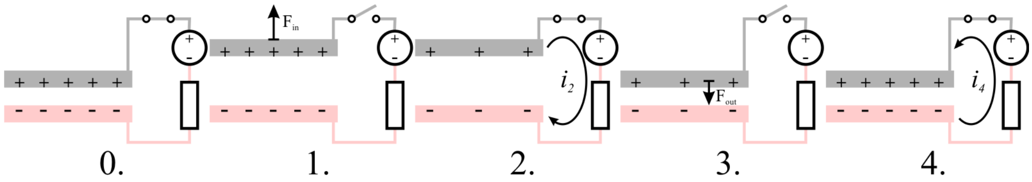

Fig. 2 The phases of extraction cycle.

0. It starts with a narrow gap between the plates, high capacitance, and fully charged with the built-in voltage U_b.

1. In the first phase the electrical contact between the plates is broken, and the top plate is moved away from the bottom plate, decreasing capacitance and increasing the voltage, while maintaining constant charge, which requires an input of external mechanical work.

2. During the second phase the capacitor is partially discharged through the resistor R, and energy is regained by converting it into output heat. It can't be completely discharged due to the presence of the voltage source U_b in the circuit.

3. In the third phase the circuit is broken again, and the top plate is allowed to be moved back into its original position by the attractive electric forces, thus performing positive output work, while releasing some of the residual electrical energy that remained in the capacitor. During this movement the capacitor voltage further decreases, but the charge content remains constant.

4. The fourth phase brings the system back into its original state, when the switch is closed and the capacitor gets recharged to the built-in voltage U_b.

The main point of this procedure is to allow the partial discharging of the electrical energy W_{c0} of the capacitor that has been accumulated by the work function difference between the dissimilar metals. Initially we assume that the discharged energy will be available for extraction from the capacitor, and more net electrical energy+mechanical work can be extracted than the mechanical work that we have to invest. If this would be possible, then the work function difference driven current would replace the extracted net energy by converting some ambient heat into electrical energy in phase 4, and cooling the metal junction. In order to know if this is possible or not, we have to calculate and analyze the energy balance of a complete cycle, which is presented below.

3.0 The Initial Charged State

Initially there is a narrow gap d_n between the plates, having the largest capacitance C_n, and the capacitor is fully charged to the built-in voltage U_b.

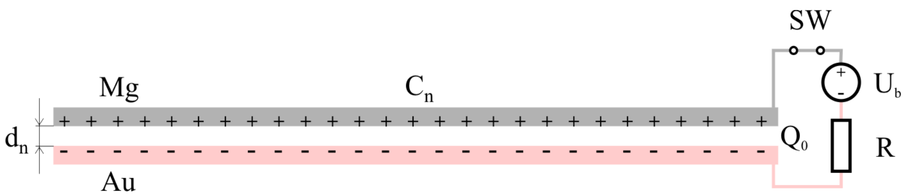

Fig. 3 The initial charged state.

The initial charge contained in the capacitor Q_0, its capacitance C_n, and its energy W_{c0} can be calculated as (S - plate surface area; ε - dielectric constant of the medium that contains the capacitor) :

$$U_0 = U_b \qquad Q_0 = C_n U_b \qquad C_n = \frac{\varepsilon S}{d_n} \qquad W_{c0} = \frac{C_n U_b^2}{2}$$

3.1 Expanding the Gap

As the first step, the switch SW is opened and the top plate is moved upward to increase the gap between the plates, while the charge in the capacitor remains constant. This wide gap $d_w = nd_n$ is taken to be n times the initial narrow distance d_n.

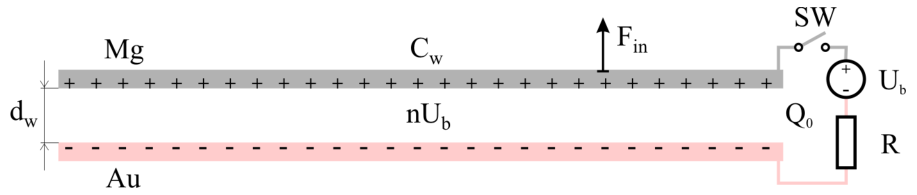

Fig. 4 Expanding the gap.

At the end of this phase the capacitor voltage increases n times, because the capacitance is decreased n times:

$$U_1 = nU_b \qquad Q_1 = Q_0 \qquad C_w = \frac{\varepsilon S}{d_w} = \frac{\varepsilon S}{nd_n} = \frac{C_n}{n}$$

The electrical energy of the capacitor also increases n times:

$$W_{c1} = \frac{Q_1^2}{2C_w} = \frac{nQ_0^2}{2C_n} = \frac{nC_n^2U_b^2}{2C_n} = \frac{nC_nU_b^2}{2} = nW_{c0}$$

The increase of electrical energy came at a cost of external mechanical work input of:

$$A_- = -(W_{c1} - W_{c0}) = -(n-1)W_{c0}$$

3.2 Discharging the Capacitor

The second phase of the cycle consists of closing the switch while maintaining the wide gap distance d_w constant. Since the voltage of the capacitor is now greater than the opposing built-in voltage U_b, a current can flow through the circuit, discharging most of the energy of the capacitor via the resistor R and voltage source U_b. After the discharge is complete there is still a voltage U_b present across the plates, which can't be further discharged due to the presence of the U_b voltage source.

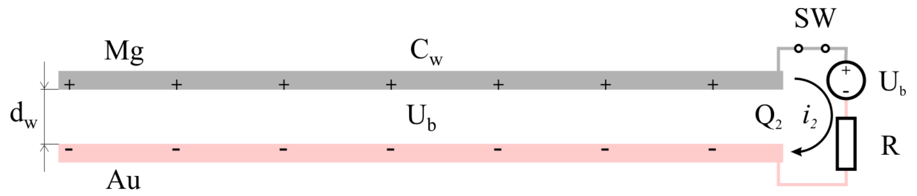

Fig. 5 Discharging the capacitor.

Thus, the capacitor voltage U_2, the stored charge Q_2, and energy of the capacitor W_{c2} at the end of the second phase are:

$$U_2 = U_b \qquad Q_2 = C_wU_b = \frac{C_nU_b}{n} \qquad W_{c2} = \frac{C_wU_b^2}{2} = \frac{C_nU_b^2}{2n} = \frac{W_{c0}}{n}$$

The output energy dissipated by the resistor W_{Rd} that we consider to be a positive gain is:

$$W_{Rd} = \Delta Q_d \frac{(U_1 - U_2)}{2} = (Q_1 - Q_2)\frac{(nU_b - U_b)}{2} = (C_nU_b - \frac{C_nU_b}{n})\frac{(n-1)U_b}{2}$$

$$W_{Rd} = \frac{(n-1)^2C_nU_b^2}{2n} = \frac{(n-1)^2}{n}W_{c0}$$

Since the current flows in the opposite direction to the polarity of the voltage source U_b in this phase, the junction now absorbs energy, instead of delivering it (analogous to the charging of an accumulator). This is considered as an energy loss for the extraction process, indicated by the negative sign. The energy absorbed by the voltage source is:

$$W_{Ub-} = -\Delta Q_d U_b = -(Q_1 - Q_2)U_b = -(C_n U_b - \frac{C_n U_b}{n})U_b = -\frac{n-1}{n} C_n U_b$$

$$\boxed{W_{Ub-} = -\frac{2(n-1)}{n} W_{c0}} \tag{1}$$

3.3 Moving the Plates Back

In the third phase the switch is opened, and the top plate is allowed to be moved down to its original position by the electric forces that attract the plates together, to recreate the narrow gap and high capacitance.

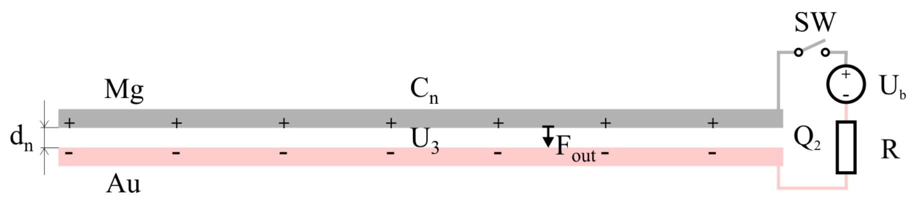

Fig. 6 The top plate is moving back to its initial position.

The charge is maintained constant, while the voltage and the energy of the capacitor are further decreased :

$$Q_3 = Q_2 \qquad U_3 = \frac{Q_3}{C_n} = \frac{C_n U_b}{n C_n} = \frac{U_b}{n} \qquad W_{c3} = \frac{C_n U_3^2}{2} = \frac{C_n U_b^2}{2n^2} = \frac{W_{c0}}{n^2}$$

During the movement an electrical force pulls the plates together, which performs useful work against an external mechanical force of resistance. Thus, some of the lost electrical energy of the capacitor is converted into mechanical work A_+ that is considered to be an additional positive output:

$$A_+ = W_{c2} - W_{c3} = \frac{W_{c0}}{n} - \frac{W_{c0}}{n^2} = \frac{n-1}{n^2} W_{c0}$$

3.4 Recharging the Capacitor

As the final 4th phase that returns the system into its initial state, the switch is closed and the capacitor gets recharged by the U_b voltage source to the initial voltage, while the narrow gap distance is kept constant.

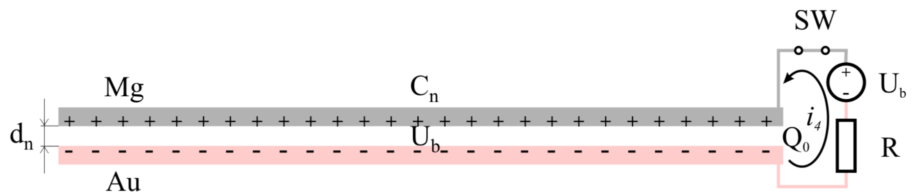

Fig. 7 Recharging the capacitor.

At the end of this recharging phase the voltage, charge, and energy of the capacitor regain their initial values:

$$U_4 = U_b \qquad Q_4 = Q_0 \qquad W_{c4} = W_{c0}$$

The charge quantity moved through the circuit during this process is:

$$\varDelta Q_{ch} = Q_0 - Q_3 = C_n U_b - \frac{C_n U_b}{n} = \frac{n-1}{n} C_n U_b$$

Since the recharging current flows through the resistor, some energy W_{Rch} will get dissipated in this phase as well, which also counts as a positive output. This energy can be calculated as the total charge moved through the resistor multiplied by the average voltage (half of the maximal voltage) across its terminals :

$$W_{Rch} = \varDelta Q_{ch} \frac{(U_0 - U_3)}{2} = \frac{n-1}{n} C_n U_b \frac{1}{2}(U_b - \frac{U_b}{n}) = \frac{(n-1)^2}{n^2} \frac{C_n U_b^2}{2}$$

$$W_{Rch} = \frac{(n-1)^2}{n^2} W_{c0}$$

In this phase the current is driven by the U_b voltage source, therefore it delivers some W_{Ub+} energy to the system, which is again considered to be positive:

$$W_{Ub+} = \varDelta Q_{ch} U_b = \frac{n-1}{n} C_n U_b^2 = \frac{2(n-1)}{n} W_{c0}$$

$$\boxed{W_{Ub+} = \frac{2(n-1)}{n} W_{c0}} \tag{2}$$

3.5 Evaluating the Net Resultant Energy Balance of the Complete Cycle

Let's extract now only those equations from above that describe the energy inputs and outputs from a consumer's point of view, and by summing them up, see if there is any net energy extracted from the system. The input/output energies of the 4 phases:

1. Increase the gap: $A_- = -(n-1)W_{c0}$ $\rightarrow -$ input work
2. Discharge: $W_{Rd} = \frac{(n-1)^2}{n} W_{c0}$ $\rightarrow +$ output heat
3. Decrease the gap: $A_+ = \frac{n-1}{n^2} W_{c0}$ $\rightarrow +$ regained output work
4. Recharge the capacitor: $W_{Rch} = \frac{(n-1)^2}{n^2} W_{c0}$ $\rightarrow +$ output heat

The sum of all these four components will give the resultant net energy gain W_g extracted from the system within a complete cycle:

$$W_g = A_- + W_{Rd} + A_+ + W_{Rch}$$

$$W_g = -(n-1)W_{c0} + \frac{(n-1)^2}{n} W_{c0} + \frac{n-1}{n^2} W_{c0} + \frac{(n-1)^2}{n^2} W_{c0}$$

$$W_g = W_{c0} \left[\frac{-n^2(n-1) + n(n-1)^2 + (n-1) + (n-1)^2}{n^2} \right]$$

$$W_g = \frac{W_{c0}(n-1)}{n^2} \left[-n^2 + n(n-1) + 1 + (n-1) \right]$$

$$W_g = \frac{W_{c0}(n-1)}{n^2} \left[-n^2 + n^2 - n + 1 + n - 1 \right]$$

$$\boxed{W_g = 0}$$

According to this result we can't extract any net energy from the capacitor using this method in a macroscopic system. This might seem to be counter intuitive, since at the end of the 3rd phase the electrical energy stored in the capacitor is $W_{c3} = \frac{W_{c0}}{n^2}$, which is only $1/n^2$th of the initial energy. If n=3 then almost 90% of the initial energy is extracted from the capacitor at this point, and only about 10% remains in it. If this is true, then where could all that 90% disappear to?

It is not difficult to recognize the correct answer to this question if we take a better look at the discharging process in phase 2. This is the point where we hope to extract the bulk of the electrical energy from the capacitor by partially discharging it through the resistor, and converting the energy into output heat. Unfortunately, while the current flows through the resistor, it also has to flow through the voltage source U_b in a reverse direction, where the U_b voltage will not add energy to the circuit, but it will absorb some instead. Now the voltage source acts as an energy sink, as if we would be charging a battery. If the metal contact was cooled during the recharging process and converted heat into electrical energy, then the same spot will be reheated during the discharge process, and dissipate the absorbed electrical energy.

Equation 2 shows how much energy W_{Ub+} is delivered by the voltage source during the phase 4 recharging; and equation 1 gives the amount of energy W_{Ub-} absorbed by the voltage source during the phase 1 discharge. Both of these values are of same magnitude but of opposite signs, therefore it is clear that there can't be any resultant net energy delivered by the voltage source.

Another even clearer and simpler explanation for the lack of net energy extraction is that within a full cycle the same quantity of charge ΔQ that moves from the top plate to the bottom, must also flow back from the bottom plate to the top through the voltage source U_b. Since the voltage of this source is constant during charging and discharging as well, and the moved charge quantity is also identical in both phases, the delivered energy $W_{Ub+} = \Delta Q U_b$ must be also identical but of opposite sign to the absorbed energy $W_{Ub-} = -\Delta Q U_b$. The energy gain in one current flow direction is the same as the loss in the opposite direction, thus no net energy extraction is possible in this macroscopic setup.

4 Conclusions

Let's briefly summarize the insights gained from this little study. It is clear that the only way to extract net energy from the built-in voltage is by using a current flow that has got at least a partial DC component flowing in the right direction to make the junction deliver energy instead of absorbing it. With other words, a DC current component supposed to flow between the plates through a contact potential difference that is less than the built-in voltage of the other contact. This seems to be impossible in an isothermal macroscopic setup without the input of external radiant energies. But if we use such radiant energies, then again the extracted power may be as much as, or less than the additional input power.

These obstacles are valid for macroscopic systems, where we assume that the speed of signal propagation is instantaneous within the system, and the instantaneous law of action-reaction prevents net power extraction. However, this obstacle may be overcome in the realm of micro- and nanometers using MEMS and NEMS systems, where the velocity of the component's kinematic movement is comparable to the velocity of charge carriers in semiconductors. The practical solutions of energy extraction proposed by Dr. Sheehan et al. [1, 2, 3, 4] are based on this speed parity in semiconductors, and on the basic principle of temporal delays between action and reaction. The discussion of these principles and their practical implementation is the subject of other papers.

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