Critique of the Paper "A Note on Solid-State Maxwell Demon" by Germano D'Abramo

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Abstract

Since Dr. Sheehan has published his discovery of the solid-state Maxwell demon (SSMD) many people have attacked the concept, simply because it violates the 2nd law of thermodynamics, which they consider to be sacrosanct and inviolable. One of the opponents is Dr. D'Abramo who attempted to debunk the principle in several papers. His main objection against the principle of the device is that according to him no electrostatic field can exist within the vacuum gap of the SSMD in equilibrium. In the present paper we will refute his arguments that he presented in the quoted publication.

Keywords: Solid-state Maxwell demon • Maxwell demon • second law of thermodynamics • thermodynamics • thermal equilibrium • nonequilibrium • semiconductor diode • n-p junction • nanotechnology • Dr. Daniel P. Sheehan • Dr. Germano D'Abramo

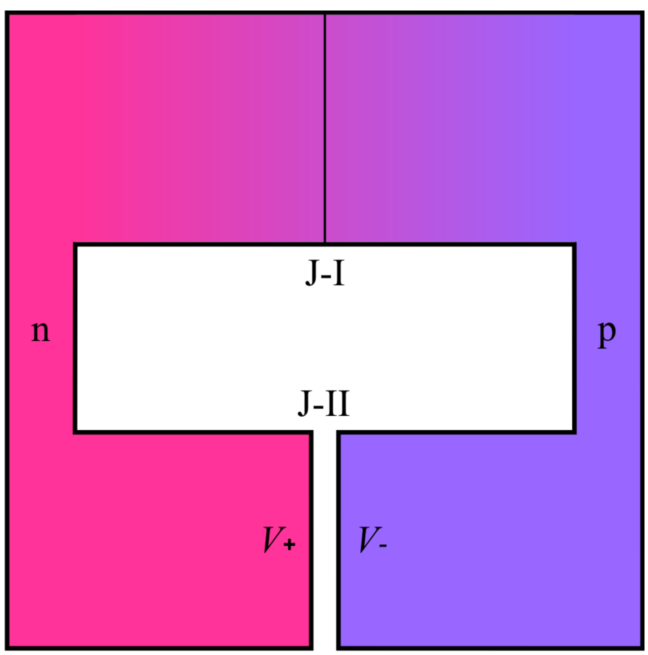

Fig. 1 One form of the solid-state Maxwell demon, called the "standard device" according to Dr. Sheehan's description. The wide depletion region at J-I junction is shaded. There is a vacuum gap at J-II at equilibrium.

1 Introduction

In the first section of Dr. D'Abramo's paper he summarizes the working principle of the solid-state Maxwell demon (SSMD), and its analysis as presented by Dr. Sheehan and his colleges in several previously published papers. One of these papers is titled: *"A Solid-State Maxwell Demon" by D. P. Sheehan, A. R. Putnam, and J. H. Wright*[1]. Only a very brief description of the SSMD will be presented here. For more details we refer the reader to the original papers [1, 2].

The solid-state Maxwell demon is a modified semiconductor p-n diode invented by Prof. Dr. Daniel P. Sheehan that violates the second law of thermodynamics. It converts ambient heat into useful mechanical work or other forms of energy, without the need for a temperature gradient. The device is a semiconductor p-n diode that consists of two symmetric horseshoe-shaped pieces of n- and p- semiconductors facing one another as shown on Fig.1.

The thermally driven diffusion current moves free charge carriers from one half of the device to the other half due to doping concentration gradients, thus creating charge separation and a depletion region next to the top p-n junction J-I. The uncompensated, bound donor and acceptor ions create a space charge and an electric field within this depletion region. This electric field drives a drift current in the opposite direction, cancelling the diffusion current at thermal equilibrium. The built-in voltage of the depletion region creates a potential difference across the vacuum gap between the two surfaces of J-II facing one another. According to Dr. Sheehan [1] the voltage drop across J-II is identical with the built-in voltage of the diode, assuming that there is no space charge and no E field elsewhere in the device, outside the depletion region. It is not the subject of this paper to discuss the validity of this assumption, however let's note that this is not correct if the doping concentrations are homogeneous. There is an uncompensated space charge and E field distribution in the bottom horizontal legs of the device as well, similar to the one in the depletion region of J-I. The difference between the two is that some of the potential drop manifests across the vacuum gap.

The novelty of the device (as compared to a common p-n diode) is in the method of extracting useful work from the electrostatic potential energy accumulated between the facing surfaces of J-II. This is achieved by a clever design of the vacuum gap between the p and n materials. If the gap size is decreased to a fraction of the depletion region's size, then the electric field intensity in the gap can be increased to become greater than that of the p-n junction J-I. The two facing surfaces of J-II can be considered as a parallel plate capacitor. According to Dr. Sheehan, the energy stored in this capacitor will be greater than the rest of energy stored elsewhere (since he assumes that all the built-in voltage is across the gap).

At least two methods have been designed so far for the extraction of useful work from the device. One of these uses a *Linear Electrostatic Motor (LEM)*[1, 3, 4], while the other is based on a *Hammer and Anvil* MEMS device [1, 3, 4, 5]. The basic idea behind these methods is to allow the electrostatic forces in the gap to periodically move objects against mechanical resistance and thus perform useful work. The periodicity of the process in the second method is achieved by (at least partially) discharging the capacitor at the end of a single stroke movement, followed by the breaking of electrical contact, and allowing the electric field in the capacitor to be recharged by the diffusion current. This way thermal energy is being extracted from the depletion region (cooled) and converted into mechanical energy at J-II, which would violate the 2nd law of thermodynamics.

Since Dr. D'Abramo is not discussing these methods in his paper, we will omit their detailed description here as well. We don't argue for or against the possibility of the proposed energy extraction methods here either, because as long as the existence of an electric field in the vacuum gap is disputed, it is meaningless to discuss methods of energy extraction from that space.

2 Refutation of Dr. D'Abramo's Arguments Against the Solid-State Maxwell Demon

At the end of introduction the author expresses his conviction that this invention can simply not work as claimed, because:

> *"We simply believe that there is no electric field in J-II and thus no positive electro-mechanical energy release is possible switching J-II gap closed."*

In Section 2 he presents two types of arguments (a heuristic and a theoretical) that aim to debunk the basic principle of the SSMD. Let's analyse first his heuristic arguments, and see how they stand up to scrutiny.

2.1 Heuristic Argument No. 1

The author uses a thought experiment imagining that the p and n halves of the semiconductor device are originally separated and not touching at J-I either. The facing p and n surfaces at the vacuum gap J-II are treated as a vacuum capacitor, and it is assumed that their surface areas can be arbitrarily large. Then he analyses what happens at the moment when the diode p and n junction surfaces are joined in junction J-I (but there is still a vacuum gap at J-II). As soon as J-I is closed, the diffusion current of free charges starts to flow, which creates a depletion region at J-I with a built-in potential difference V_{bi}. According to Kirchhoff's loop rule this diffusion current must flow trough the device moving free charges from one plate of the J-II capacitor to the other, until equilibrium is established.

The first heuristic argument against the basic principle of SSMD is:

> *"It is easy to see that this current can be made arbitrarily high in intensity (if the ohmic resistance R of J-I is suitably low) and/or arbitrarily long in duration (high RC time constant), since S_{face}, and thus $Q_{J-IIface}$, can be arbitrarily high. All this is somewhat 'unrealistic': J-I can even melt if its section and ohmic resistance R are the right ones; or cool down to extremely low temperatures, since the energy needed to maintain the current flow should come from the thermal agitation in J-I."*

The imaginary theoretical claim that the p and n surfaces in J-II (treated as "capacitor plates") can be arbitrarily large is an unrealistic expectation; therefore it is completely natural that it will have unrealistic expected consequences. Using the argued impossibility of such unrealistic consequences as a proof, or even meaningful argument against the principle of SSMD is a straw man argument. It makes no logical sense.

If only the capacitor plates of J-II are made to be very large, but the junction surfaces at J-I in the diode are relatively small, then the diffusion current that is charging the capacitor plates can not be arbitrarily high, but it has got a relatively low finite value. Even if the surface area of the diode junction at J-I is made to be as large as that of the capacitor surfaces at J-II, we still have to consider the current density instead of the total current intensity, if we want to evaluate the possibility of junction melting. This current density depends on the free charge concentration gradient, and for electrons it can be calculated as $J_n = eD_n dn/dx$; for holes it is $J_p = -eD_p dp/dx$. A typical value is about $2A/mm^2$, which is not that high to threaten melting the material.

But even if we assume that by some special techniques we can raise the diffusion current density to such a high level that the dissipated heat in the junction would elevate the local temperature to the melting point, this still doesn't represent a valid argument against the basic principle of the SSMD. It would just mean that the device would start to work and charge the capacitor at J-II as expected and described by Dr. Sheehan, until the melting of the junction. The melting of the junction is simply an undesirable consequence of poor design, and by no means a proof that the underlying principle of the SSMD is wrong.

Besides the limited current density, there is one more natural limiting factor that opposes the overheating and melting of the junction, namely the fact that heat is being converted into electrical energy, and thus the junction is getting cooled by the process. The author uses even this phenomenon, the cooling by heat energy conversion as a debunking argument, saying that the junction could even *"cool down to extremely low temperatures"*, which according to him supposed to discredit the principle of the device.

As long as the first law of thermodynamics is valid, and heat is being converted into other forms of energy in the device, the diode will cool down. The degree of cooling is limited though, simply by the self regulating mechanism of reduced thermal motion of the charge carriers at lower temperatures, and by reduced diffusion current density. But again, even if it would cool down to an "extremely low temperature" that fact would still not contradict the working principle, but reinforce it instead, because such cooling is possible only if the principle is correct. The continuous operation of a practical device requires a continuous thermal power input equal to the extracted electrical or mechanical power, but this is only a design problem, not a principal obstacle.

2.2 Heuristic Argument No. 2

The second heuristic argument of Dr. D'Abramo is based on the analogy between the SSMD and two electrically connected metals with different work functions. In this thought experiment the author describes a huge parallel plate capacitor with one of its plates made of copper, and the other made of zinc. The capacitor can be arbitrarily large, having an arbitrarily high capacitance. The capacitor plate made of zinc is connected to another smaller zinc plate with a zinc wire; while the other capacitor plate made of copper is connected to another smaller copper plate with a copper wire. The metals are kept at a uniform temperature in order to avoid charge accumulation due to the Seebeck/Thomson effect. The plates and wires are initially neutral, and the plates are not connected to each other through the wires, as shown on Fig. 2a.

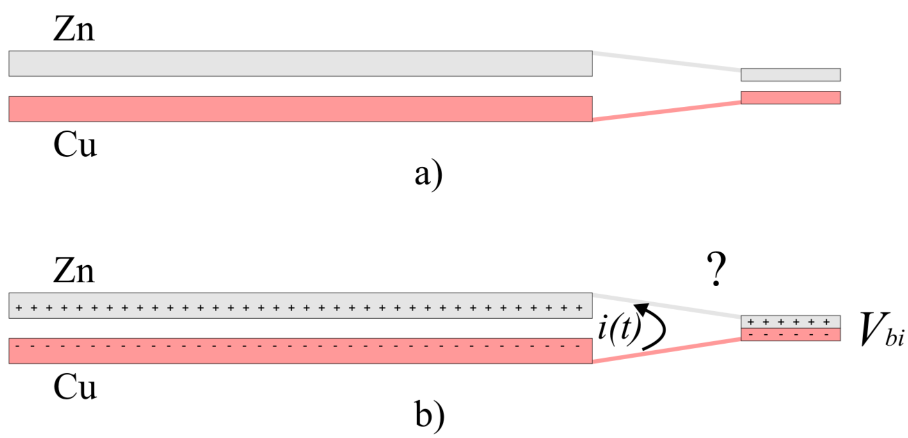

Fig. 2 Illustration of heuristic argument No. 2 thought experiment.

When the two small plates (or even bare wires) are connected, a Cu-Zn junction is created at the contact surface with a very thin depletion layer, see Fig. 2b. The diffusion current will create a contact potential difference V_{co} between the two different metals. According to the principles of SSMD the same potential difference V_{co} must appear between the two plates of the large capacitor as well. Consequently, a large amount of charges will accumulate in the capacitor. The second heuristic argument is:

> *"As before, all this implies that an arbitrarily high current in intensity and/or arbitrarily long in duration must flow through the wires and that the small Cu-Zn junction must cool down very fast and significantly."*

The non-arguments of arbitrarily large currents and significant fast cooling have been already refuted above. Next, Dr. D'Abramo employs an authoritative claim referring to several other sources in his efforts to support his statements:

"This behavior does not match what happens in laboratory experiments and in the real world. It is already well known that this is not what really happens (see the Volta effect [8])."

The authors of the reference paper [8] don't measure temperature, they explore only the measurement of contact potential. They don't claim that cooling doesn't take place. They don't claim that the contact potential difference between the two dissimilar metals touching each other exists exclusively within the extremely thin depletion region either. Germano's claim that this document supports his arguments is simply false.

Next, Dr. D'Abramo explains the reason why he thinks that the capacitor of this thought experiment (and that of SSMD) can not be charged by the diffusion current. He thinks that when two metals with different work functions (and similarly, when an n- and a p- semiconductor) are electrically connected, the diffusion current is localized exclusively within the thin depletion layer in thermal equilibrium. He argues that outside this depletion region there is no free charge accumulation. In order to support his claim, he refers to a classical laboratory experiment, and three papers that supposed to prove the validity of this explanation:

"A simple laboratory experiment with Cu and Zn plates and a gold-leaf electroscope can confirm such a behavior [6,7]. Only when the two metals are removed apart the charges, initially localized within the depletion layer, are free to spread across the surfaces of the metallic plates [6,7,8], satisfying electrostatic equi-potentiality", see Fig. 3.

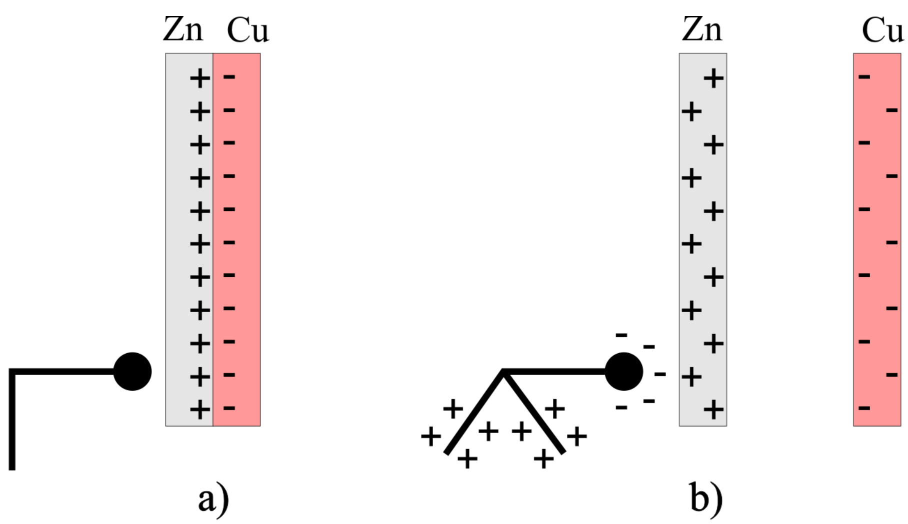

Fig. 3 Illustration of the alleged non-existence of contact potential difference outside the depletion region while the different metals are in electrical contact with each other.

The law of equipotentiality of conductors is always satisfied in electrostatics (when there is no current flow) in the absence of internal electric fields and non-electric charge separating forces. The charge separating forces present in the depletion region that drive the diffusion current are driven by thermal energy (and by the charge concentration gradient in semiconductors). Since this force is non-electric in nature, it can create an electric field inside a conductor, within the volume where it is active, even in a static case of equilibrium. This is possible only within the depletion regions, because the forces exerted upon the free charges by the internal electric fields are opposed by the non-electric forces of diffusion, and thus a static equilibrium can be maintained. Due to the presence of the electric field within the depletion region (maintained by diffusion), a potential difference can exist between the contact surface and the rest of metal even in static case. However, outside the depletion region, everywhere else within the conductor, and on its surface, the law of equipotentiality rules (because internal electric fields that could alter the potential, which are not compensated by non-electric forces can't exist). This law of equipotentiality is always in effect for metals in electrostatics; not only after the different metals are separated (as Dr. D'Abramo claims), but also while they are in contact.

The setup illustrated on Fig. 3a is analogous to a parallel plate capacitor with a battery of say 1V connected to its terminals. The depletion region of the Fig. 3a corresponds to the battery that contains non-electric forces, which separate the charges and create an internal electric field. This electric field creates a potential difference across the terminals of the battery, and also across the connected capacitor plates. If we try to measure this 1V (or less) potential difference between the plates with a gold leaf electroscope, it will not detect any voltage or any charge. This doesn't mean that such voltage does not exist, but it means only that the metal leaf electroscope's sensitivity is not good enough to detect such a low voltage.

Fig. 3b is analogous to the situation when (after charging the capacitor in our analogy) the battery is disconnected from the capacitor, and the distance between its plates is increased. The charged plates of the capacitor can be moved apart only by performing mechanical work and increasing the energy stored by it in the process. Due to this increased energy the potential difference across its plates will also increase to a level that could be detected or even measured by a gold-leaf electroscope. But the fact that the electroscope now indicates the presence of an electric potential doesn't mean that the law of equipotentiality started to work only after moving the plates apart.

The fact that most of the charges on Fig. 3a are accumulated on the surface borders of the depletion region (inside the metal) doesn't mean that there are no uncompensated free charges elsewhere on the external surfaces of the plates. Actually the Fig. 3a (based on the original in [2]) is wrong, because it supposed to show at least one or two positive and negative charges on the external surfaces of the plates, indicating the presence of a weak surface charge. In fact such surface charges must exist in order to satisfy the law of equipotentiality, and keep the bulk internal volume and external surface of the plates at the same potential as that of the depletion region's edge (farthest from the contact surface). Even though the surface charge density on the external surfaces of the capacitor is much less than that on the borders of depletion region, it is still enough to create the same contact potential difference between any two points on the two different plates, due to the longer electric field lines that stretch between them.

When the plates are moved apart, the originally very small distance between the charges of opposite polarity (on the border surfaces of depletion region) is increased, and becomes comparable to the length of the electric field lines that connect the opposite charges on the external plate surfaces. In order to keep the line integral of $V = \int \mathbf{E} \cdot d\mathbf{l}$ identical between any two ends of E field lines, charges must move from the dense regions to the external surfaces, and thus a charge redistribution takes place. But again, the 'spreading of charges' during the separation doesn't mean that there were no uncompensated free charges on the external surfaces of the plates before the separation.

Also, the charge density at a specific point does not determine its electric potential in itself. The potential difference between two points does not only depend on the charge density at these points, but also on the length of the electric field line that connects them. Therefore, the external surfaces of the plates (having low charge density, but long E field lines) on Fig. 3a can be at the same potential as that of the depletion region's edge (with highest charge density, but shortest E field lines).

In order to support the argument presented in Germano's last quote, he refers to three documents [6, 7, 8] that supposed to confirm its validity. It has been already explained above that reference [8] doesn't support his claims. Reference [7] is actually another paper written by Germano, which by the way refers back to the paper that is the subject of this refutation [2], claiming that it contains the disproof of the SSMD's working principle. Therefore paper [7] is a circular reference (and argument). In reference [6] we can find this statement:

> *"In 1799, he [Volta] carried out the first measurements of contact voltage between metals, a phenomenon which is only measurable when the contact is broken..."*

Perhaps Dr. D'Abramo has taken this at face value, and this is the source of his confusion. This is a misinterpretation of the observations. The electrostatic voltmeter used by Volta (metal leaf electrometer) was not able to measure or even detect a low voltage of 1V without first amplifying the potential difference by separating the electrodes of the capacitor that carried the charges. This is the reason why he could measure the very low contact potential only when he amplified the voltage by breaking the contact between the dissimilar metal plates of the capacitor and increasing the distance between them. The low contract voltage between metals is however measurable with today's sophisticated electrometers even without braking the contact between the metals.

2.3 The Theoretical Argument

In his theoretical argument the author describes the Faraday's law and/or Kirchhoff's loop rule as being based on the more fundamental law of energy conservation:

> *"Conservation of energy demands that a test electronic charge e conveyed around a closed path γ in the device bulk of Fig. 1, through J-I and J-II at equilibrium, must undergo zero net work from all the forces present along the path."*

This is a false statement. The Faraday's law and/or Kirchhoff's loop rule are valid only in electromagnetics, which does not include other phenomena like mechanical, thermal, chemical etc. forces. One can not derive the Kirchhoff's loop rule from the law of energy conservation if other than electromagnetic forces and phenomena are also included in the derivation. One can't add together apples and oranges and expect to arrive to a correct result. The correct form of Faraday's law and/or Kirchhoff's loop rule can be derived from the law of energy conservation only if the derivation is restricted to contain only electromagnetic forces. However, Germano wants to include the effects of all types of forces into the Kirchhoff's loop rule that are present along the path. This is faulty logic, which is analogous to the mixing of apples with oranges. The correct form of the above quoted statement is:

> *'Conservation of energy demands that a test electronic charge e conveyed around a closed path γ in the device bulk of Fig. 1, through J-I and J-II at equilibrium, must undergo zero net work from all the* ***electrical*** *forces present along the path. This excludes all forces that don't originate from the electric field.'*

The mathematical equations (2), (3) and (4) of the author are based on the false premise that since the sum of all the work performed by **all types** of forces along the closed loop must be zero, and since the **two different types** of forces present in the depletion region (the electric and the diffusive/thermal forces) are equal and opposite (already summing up to the expected net zero), there can't be any electric field in the vacuum gap. As already mentioned, when deriving the Kirchhoff's loop rule, only the electric forces may be included, and all other types of forces must be excluded from the equations. Otherwise the faulty logic will lead to wrong results and wrong conclusions.

In order to ease the understanding of this fallacy let's consider the following analogy, which is equivalent to the author's argument and thought process. There is a similar rule in physics, according to which the net sum of all the work done by gravitational forces upon a mass is zero, when it is moved along a closed path (the force field is conservative). Now if we distort this rule (in a similar fashion as Germano did with the Kirchhoff's loop rule) and include **all different types** of forces that can act on the mass along the path, then we can have the following weird situation.

We could have a man lifting up a ball from the ground, thus exerting a mechanical force on the ball while performing work, and placing the ball on a table. At the same time a gravitational force acted upon the ball in the opposite direction that was about the same as the mechanical force, and which performed the exact same but negative work on the ball (absorbed work) as the man did. Now the question is that if we roll the ball to the other end of the perfectly level and smooth table (without work) and roll it off the table top, will there be a gravitational field present there or not?

According to the faulty logic, the combined net work done by the man and the gravitational field while lifting the ball is already zero. Since the only other place where work could be done along the closed loop by the gravitational forces is the other side of the table (assuming perfectly smooth and level ground), according to the faulty all inclusive loop rule, there can't be a gravitational field present at the other side of the table. If there would be gravitational forces there, then the total sum of work done by **all different** forces on the ball would not be zero when moved in a closed loop, which would contradict the faulty closed loop rule. This would mean that the ball would just have to float in the air, and not fall back to the floor.

Returning to the case of SSMD, the correct application of Kirchhoff's loop rule is to treat the electrical and diffusive forces separately, and consider only the electrical forces for the loop rule. In order to simplify the explanations, let's assume at this point that the whole V_{bi} appears across the gap of J-II, as claimed by Dr. Sheehan in [1] (which is not correct). Since according to Dr. Sheehan [1] there is no electric field inside the semiconductor outside the depletion region, the only other place it could exist is the vacuum gap between the faces of J-II. In order to obtain a net zero work **done by the electric fields** when moving a charge along a closed loop crossing J-I and J-II, there must be an electric field present in the gap. With other words, the work done by the electric field in the depletion region must be the same (but of opposite sign) as that done by the electric field in the gap of J-II, when moving a charge in the discussed closed loop. The intensity of the gap's E field must be such as to create the same built-in potential difference across the gap faces as that which is present across the depletion region. Therefore the narrower the gap, the higher the E field intensity, which is exploited by the SSMD principle.

If there would be no uncompensated space charges in the device outside of J-I depletion region (as Dr. Sheehan and Dr. D'Abramo assumed), the correct application of Kirchhoff's loop rule in mathematical form would be:

$$\oint_{\gamma} dW_{el} = 0 \tag{1}$$

$$\int_{J-I} eE_{bi} d\gamma + \int_{J-II} eE_{J-II} d\gamma = 0 \tag{2}$$

$$e\int_{J-I} E_{bi} d\gamma = -eE_{J-II} x_g \tag{3}$$

$$V_{bi} = -V_g \tag{4}$$

Even though it is not the subject of this paper to discuss the validity of all the statements made by Dr. Sheehan in some of his related papers [1,4], it is important to realize that contrary to his assumption, in reality there are uncompensated space charges outside the diode's J-I depletion region. This space charge creates an E field, and a depletion region in the bottom horizontal legs of the device as well that are similar to those of J-I. The difference between the two regions is that there will be a potential difference across the vacuum gap creating an intense E field there, therefore there will be less voltage drop across the space charge regions in the bottom legs than across the depletion region of J-I. Consequently, not all the built-in voltage will appear across the gap, but only part of it. This is unfavourable for the purpose of possible energy extraction, but some solutions might still exist for bypassing of this difficulty.

The space charge density and E field intensity graphs on Fig. 2 of references [1,2,4] are incorrect as well. The correct graphs of these fields are shown here in Fig. 4:

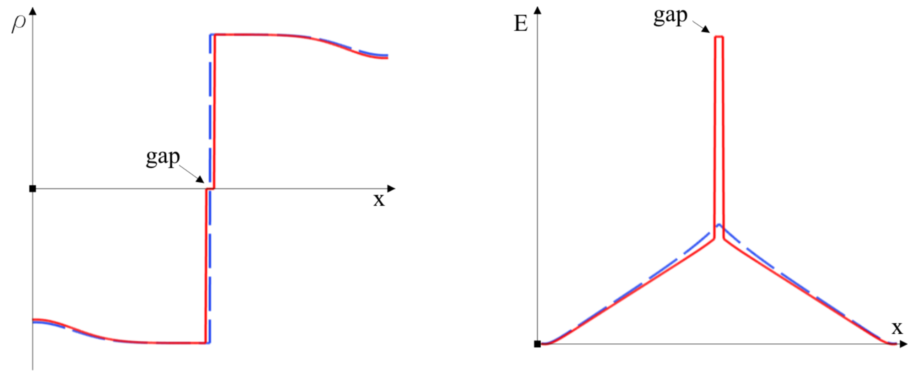

Fig. 4 The realistic graphs of space charge density ρ (left), and E field intensity (right) distributions in the 'standard device' of SSMD. Blue dashed line – across top depletion region of J-I; red line – across bottom horizontal legs. (Dimension proportions are slightly different than on Fig. 1).

What about the work done by the diffusive forces while moving the diffusion current and charging up the capacitor of J-II? Doesn't that violate the law of energy conservation? It does not. The energy comes from the thermal energy of the material via the process of diffusion. If this is converted into other forms of energy and extracted, then the diode will cool down. Thus, the law of energy conservation remains valid for the whole system, including all different types of forces, and all different types or energies. It is unnecessary to distort the Kirchhoff's loop rule in order to enforce the law of energy conservation.

As for the 2nd law of thermodynamics, if clearly measurable facts prove it's invalidity under specific circumstances, then it is foolish to stick to old dogmas. Nature is the highest authority on the real (not theoretical) laws of physics. Ignoring these real laws in order to maintain the old status quo only retards the advancement of science.

3 The Electric Field around a P-N Diode

Strangely enough, it is quite difficult to find a realistic picture of the external electric field surrounding a p-n diode in literature or online. This might be a contributing reason why many people think that such a field doesn't exist, and they assume that any E field is strictly confined to the depletion region inside the semiconductor. This is a similar misconception to the assumption that there is no electric field outside of a parallel plate capacitor if the gap between its plates is very narrow. Such misleading ideas originating from rough approximations are often further strengthened by figures in some textbooks that illustrate these misconceptions.

Let's contribute to the remediation of this distorted situation by including two images that illustrate the fields surrounding a semiconductor diode, as they really are. These images show a silicon p-n diode surrounded by SiO_2 (insulator) at thermal equilibrium (without any external bias) with a low doping concentration of constant density in both p and n halves. The first image shows the electric potential field distribution inside and around the diode, see Fig. 5. The depletion region is quite well visible near the junction, because it is fairly wide (about 1/5th of diode's length) due to the low doping concentrations. This region spreads from the edge of deep blue to the edge of deep red, and it is covered with the colours of the rainbow. It nicely illustrates that the potential is nearly constant everywhere inside the semiconductor, but outside the depletion region.

The reason we use the 'nearly' word here is because in cases of very low doping concentrations there will be a thin space charge near the surface (instead of a strict surface charge that is observed in conductors). This thin space charge will allow some electric field lines to shallowly penetrate into the semiconductor through its surfaces. However, the bulk of the volume inside the semiconductor, outside the depletion region is practically at the same potential, which is indicated by the same colour.

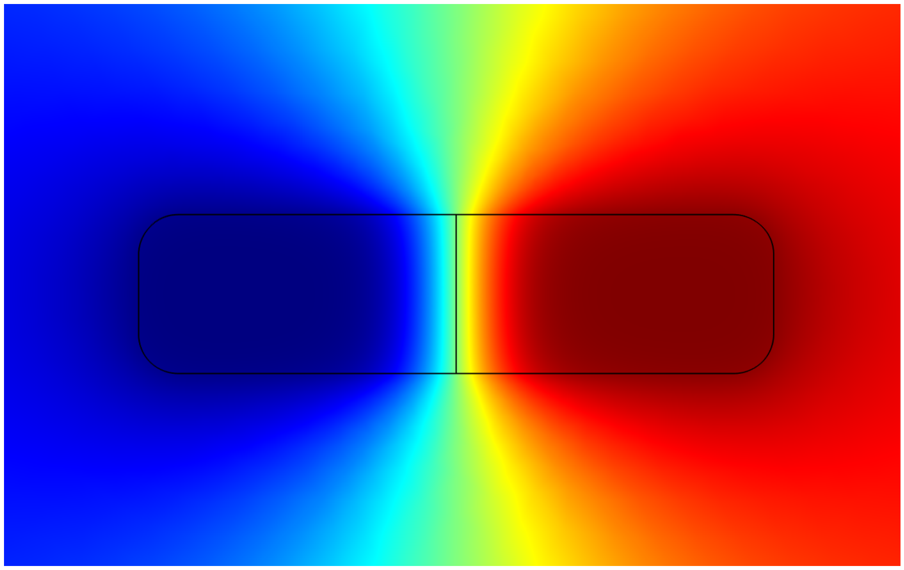

Fig. 5 The potential field distribution of a silicon p-n diode with low doping concentration.

On Fig. 6 the electric field of the same diode is visible. In order to display as much detail as possible, only the left half of the diode is shown. The brightness of the colour and the length of the E field vector arrows indicate the local E field intensities. The orientations of the arrows represent the local E field vector directions. The scale of the arrow length is logarithmic in order to show the weak, but still present E field near the surfaces inside the semiconductor as well (where the thin space charge is present).

We can see from this image that there is no E field deep inside the semiconductor, outside the depletion region (or it is extremely weak). It is also visible that the greatest E field intensity is at the line of p-n junction and it becomes nearly zero at the (somewhat smeared out) edges of the depletion region. But the main point of these pictures is to show that there is a static E field surrounding the diode in the insulator (or vacuum) that surrounds the semiconductor. This also means that there are free charges on and near the surfaces of the semiconductor (within the thin space charge regions). These free charges create a potential difference across the two ends of the diode semiconductor, which is nearly equal to the built-in voltage in this setup. One could argue that these E fields are not created by free charge carriers, but rather by the bound uncompensated donor and acceptor ions. However, these bound ions become uncompensated only when free charge carriers move in or out of that region, thus it is the same phenomenon expressed with different terminology.

If we would bend the two ends of the diode in the shape of the SSMD, and make the gap between the end faces very narrow, then we could have a very intense E field within that gap, as it has been described in the referenced papers of Dr. Sheehan. But by doing so, the internal space charge distribution and E fields outside the diode junction's depletion region would also change, and only a fraction of the built-in voltage would appear across the gap, as explained above.

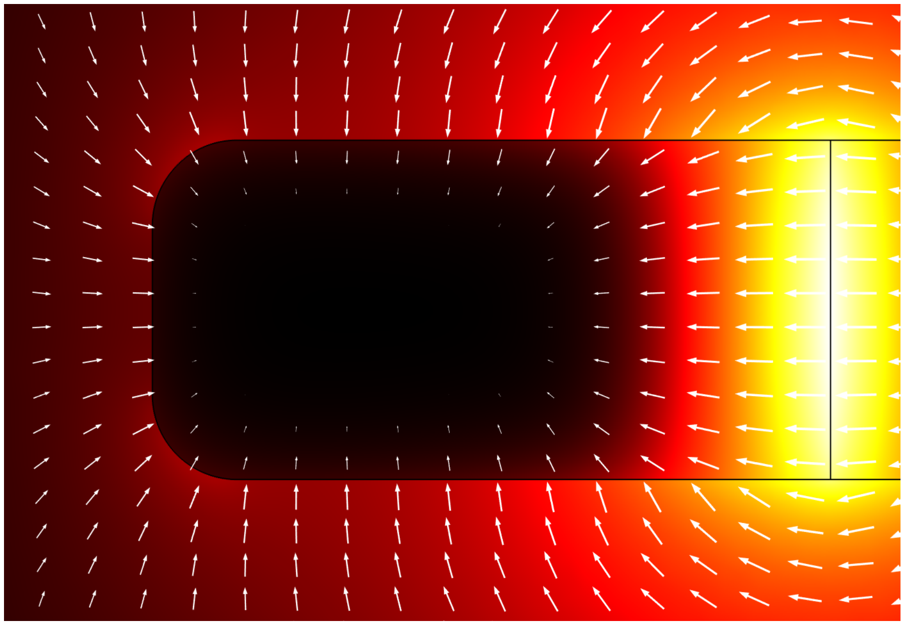

Fig. 6 The electrostatic field distribution of a silicon p-n diode with low doping concentration.

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