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On the Absence of Carrier Drift in Two-Terminal Devices and the Origin of Their Lowest Resistance per Carrier $R_K = \hbar/q^2$

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ABSTRACT

After a criticism on today's model for electrical noise in resistors, we pass to use a Quantum-compliant model based on the discreteness of electrical charge in a complex Admittance. From this new model we show that carrier drift viewed as charged particle motion in response to an electric field is unlike to occur in bulk regions of Solid-State devices where carriers react as dipoles against this field. The absence of the shot noise that charges drifting in resistors should produce and the evolution of the Phase Noise with the active power existing in the resonators of *L-C* oscillators, are two effects added in proof for this conduction model without carrier drift where the resistance of any two-terminal device becomes discrete and has a minimum value per carrier that is the Quantum resistance $R_K = \hbar/q^2\ \Omega$.

Keywords: Fluctuation-Dissipation; Energy Conversion into Heat; Two-Terminal Device; Discrete Resistance; Capacitance; Shot Noise; Quantum Hall Resistance

1. Introduction

Few years ago, the work entitled: "*On the first measurement of shot noise in macroscopic resistors by J. B. Johnson*" was rejected on the basis of the empirical absence of shot noise associated to a DC current in macroscopic resistors. Taking this absence as a type of dogma, the rejection report stated: "*Shot noise in resistors has never been observed up to now. There is no shot noise* (*proportional to the DC current*) *on top of the thermal noise. If some increase in thermal noise was observed by passing a current through the sample compared to the thermal noise without current through the resistor then it was due to a temperature increase of the sample. The classical way to explain the non existence of shot noise in resistors is to model the resistor by a large number of N diodes in series each with noise source 2qI parallel to a dynamic resistor r_d. This results in a negligible current noise for $N \to \infty$ as shown in*:

$$S_I = \frac{N2qIr_d^2}{\left(Nr_d\right)^2} = \frac{2qI}{N} \tag{1}$$

Since scientific dogmas use to be replaced by better ideas (not necessarily new ones) excelling them in some way, let us summarize the main contributions of this paper by rewriting these statements as: "*Shot noise in resistors is observed routinely but disguised as Johnson noise. It comes from those electrons that pass randomly between terminals in Thermal Equilibrium* (*TE*). *There is no shot noise* (*proportional to the DC current) on top of the Thermal Noise* (*TN*) *because DC current is Switched Current that uses carrier polarization to emulate Resistance each time an electron passes between terminals. Thus*, *conduction current does not need electron passages other than those that already exist in TE. If some increase in TN was observed by setting a DC current in the resistor compared to its TN without this current in the device*, *then it was due to a temperature increase of the device. The way these results are obtained is by using a Physical model for the resistor that shows why carrier drift is not a cogent mechanism to explain the conduction currents measured in Two-Terminal Devices* (*2TD*) *neither the Joule Effect associated to them*".

Since this paper is related with Instrumentation and Measurement let us define DC current and conduction current from the key role of the 2TD where they can be measured. Note that electrical current always is measured in a 2TD, not "in a material" as most people assume naively. Conduction current $i_P(t)$ is *current in-Phase* with a sinusoidal voltage $v(t)$ between terminals of the 2TD. A different current also measured in a 2TD is its reactive current $i_Q(t)$ found in-Quadrature with $v(t)$. It is worth noting that *when electrons pass* between terminals of a 2TD, they *generate shot noise* as it was observed long time ago [1,2] and this passage requires reactive currents $i_Q(t)$ in the 2TD (e.g. displacement currents), not conduction ones $i_P(t)$.

With regard "DC current", it is conduction current appearing when frequency $f \rightarrow 0$. In this case we have: $v(t) \neq 0$ and $\partial v(t)/\partial t = 0$, thus $v(t) = V_0$, constant or *static* during the measurement. The null derivative $\partial v(t)/\partial t = 0$ suggests that no net displacement current is required to have DC current, or that there is no need for a net flux of charges crossing the 2TD. The sinusoidal forms of $v(t)$, $i_P(t)$ and $i_Q(t)$ refer to the Fourier components of arbitrary voltages and currents in a 2TD. Thanks to less dogmatic referees, the reason why J. B. Johnson [3] already measured shot noise in 1928, can be read in [4] that not only explains why "*Shot noise in resistors appears disguised as Johnson noise in TE*", but also gives a Quantum compliant model for electrical noise in 2TDs that agrees with the Quantum treatment of noise published by Callen and Welton in 1951 [5]. Readers wishing to know more about the use in 2TDs of the Fluctuation-Dissipation Theorem derived from [5], could find [6] of interest.

This paper is organized as follows. Section 2 criticises today's model of electrical noise in resistors based on a lonely resistance R (conductance $G = 1/R$) driven by its Nyquist noise density $i_n^2 = 4kT/R\ \mathrm{A}^2/\mathrm{Hz}$. This reflects the partial understanding of [7] shown in [4,6]. From the new model of [4], Section 3 shows that Joule effect is a Conversion of electrical energy into heat that differs from the Dissipation of electrical energy in the context of [5] because electrical energy converted into heat by Joule effect comes from a static field between terminals, but the energy Dissipated accordingly to [4-6] comes from thermal energy of the carriers previously converted into electrical one by a transducer that exists in the 2TD. Finally, some conclusions are drawn at the end.

To end this Introduction let us consider the system used to interact with a material (vacuum included [8]) in electrical measurements. We mean the 2TD that appears in **Figure 1** for a one-dimensional (1-D) treatment of the electrical conduction in 2TDs like resistors. It is worth noting the *capacitor* formed by the two terminals (plates D-D) of high conductivity ($\sigma \rightarrow \infty$) used *to apply* electric fields to the material or *to sense* electric fields between terminals of this 2TD like its Fluctuations of electric field we called Thermal Actions (TA) in [4]. Hence, the terminals of a 2TD are *connected by any electric field* appearing between them, in such a way that a Fluctuation of charge appearing on one terminal bears with it a *simultaneous* Fluctuation (with opposed sign) of charge in the other. Since $v(t)$ is the difference of two electrical potentials that appears simultaneously at terminals D-D in **Figure 1**, *the capacitance C between terminals is the key element* that links Cause (Fluctuations of charge in *C*) with its measurable Effect that is $v(t)$. This key role does not depend on the resistance R between terminals and it allowed us to tell that Johnson noise of Solid-State resistors measured in V^2/Hz is the Effect of a Cause (charge noise *power* in C^2/s, Nyquist noise density in A^2/Hz) that is the shot noise *density* of electrons passing randomly between the plates of *C* in the resistor [4].

2. Criticism on Today's View about Thermal Noise in Resistors

Figure 1 also shows the starting point of the microscopic model widely accepted for the electrical conduction in Solid-State devices. This model considers electrons as particles moving randomly through the material between terminals of a resistor with thermal velocities $v_{th} \approx 10^8$ cm/s at room T (T = 300 K). Thus electrons are considered as particles colliding with the material (thus within its volume) with a mean collision time τ_{coll} of ps typically). This gives a mean collision path $\lambda_{coll} \approx 1$ µm, much lower than the length L of macroscopic resistors. This model where charged particles of mass m^* or *carriers* relax kinetic energy by collisions with relaxation time τ_{coll} leads to a Lorentzian spectrum for the spectral density of current fluctuations (in A^2/Hz) that is:

$$S_I(f) = \frac{4kT}{R} \frac{1}{1 + \left(\frac{f}{f_c}\right)^2} \qquad (2)$$

where $f_c = 1/(2\pi\tau_{coll})$ and R is the Resistance that Ohm's law gives for this parallelepiped of material, which is inversely proportional to the conductivity σ of the homogeneous material between terminals D-D of **Figure 1**. It is worth noting that Equation (2) is not Nyquist formula with Plank's constant [7], but the so-called Lorentz spectrum, flat below the characteristic frequency f_c ($f_c \approx 10^{12}$ Hz) and proportional to $1/f^2$ for $f \gg f_c$.

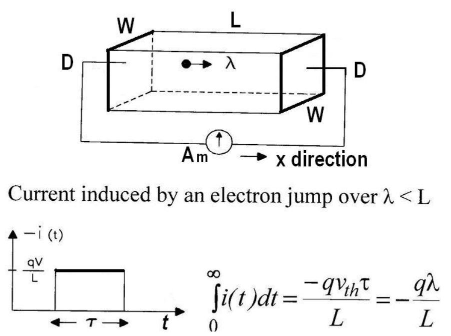

Figure 1. Geometrical view (1-D) of a resistor made from a parallelepiped of material ended by two highly conducting "plates" or contacts.

Because for $f \ll f_c$ Equation (2) gives the Nyquist density $4kT/R\ \mathrm{A}^2/\mathrm{Hz}$, τ_{coll} tends to be considered as the more fundamental parameter to take into account the Brownian motion process underlying TN in resistors. This way, Equation (2) is considered as a microscopic explanation of Nyquist result and thus, the circuits used today to represent a noisy resistor remain those that were derived from [7] long time ago. They are in **Figure 2**, where the lonely resistance R seeks to represent a noiseless resistor whereas a noisy one is represented by this R together with a noise generator in parallel or in series (Norton and Thèvenin equivalents).

However, we have shown in [6] that the Brownian motion process that really matters for electrical noise is the charge noise in C that Equation (2) does not consider at all. Because electrical noise requires the presence of electrical energy in the 2TD, the thermal origin of the electrical noise explained by Nyquist [7] suggests the presence of a Transducer#1 in the 2TD converting kinetic energy of the carriers into electrical energy that, *Fluctuating and being Dissipated* in the 2TD accordingly to [5], would produce its electrical noise. Transducer#1 is no other than C [4], which also is the store of electrical energy we had to propose in [9] for Solid-State resistors and for reactive 2TDs associated to space charge regions that modulate their resistance so as to produce their $1/f$ "excess noise". Since the collision model does not consider these facts, Equation (2) is unaware about the quantum mechanical factor given by Nyquist that is:

$$\frac{hf}{e^{hf/kT}-1} \approx \frac{hf}{1+\dfrac{hf}{2kT}+\cdots-1} \Rightarrow f_Q \approx \frac{kT}{h}\left(\approx 6\ \mathrm{THz\_}at\_T = 300\ \mathrm{K}\right) \quad (3)$$

where k is Boltzmann constant, T is temperature and h is Plank constant. The noise densities $i_n^2 = 4kT/R\ \mathrm{A}^2/\mathrm{Hz}$ (Nyquist noise) and $e_n^2 = 4kTR\ \mathrm{V}^2/\mathrm{Hz}$ (Johnson noise) used in **Figure 2** as i_n and e_n are constant up to frequencies f_Q where Equation (3) departs from $2kT$. Since the typical $\tau_{coll} \approx 1$ ps found in the literature means that $S_I(f)$ drops around $f_c \approx 0.16$ THz, the high ratio $f_Q/f_c \gg 1$ suggests that electrons "collide" or interact in a very different way.

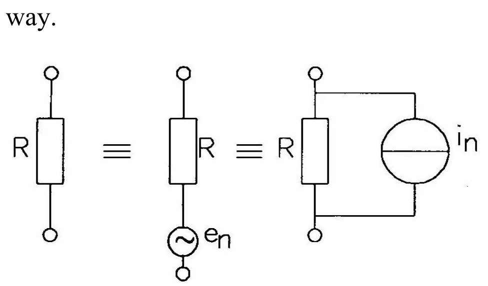

Figure 2. Electrical circuits derived from a simplified view of Figure 1 that are widely used in noise calculations.

From the analogy of this collision model with the kinetic theory of gases and from the drift model that it requires for electrical conduction we have to admit that the material existing between plates D-D in **Figure 1** contains a gas of charged particles, each carrying a charge $-q \approx -1.6 \times 10^{-19}$ C. This gas is embedded in the material in such a way that these carriers can interact with the lattice but not among themselves. By this we mean that these electrons moving randomly generate electrical noise as the title of [7] suggests due to their electrical charge, but for the same reason, they would have to repel mutually. This makes hard to believe that these charged carriers remain within the material without colliding electrically among themselves to escape quickly towards its surfaces. The dielectric relaxation time $\tau_d = \varepsilon/\sigma$ of the material between terminals of **Figure 1** that links its dielectric permittivity ε with its conductivity σ, reflects the speed of this escape process and also gives a good reason to contend that if an electron exits in the form of a carrier within the bulk region of the 2TD of **Figure 1**, it *will not be a unipolar charge*, but a *distributed dipole* that, from time to time, will appear as a long-range dipole on the terminals of the 2TD, thus on its "surfaces" for the 1-D treatment we are employing.

Another meaning of τ_d from the device viewpoint is that a resistor with the shape of **Figure 1** will shunt by a capacitance $C_d = \tau_d/R$ the resistance R it offers between terminals due to its material [9]. This shows that **Figure 1** is not complete since it lacks an electrical dipole appearing each time an electron is suddenly displaced within its volume. Added to this, **Figure 1** also assumes that electrons can pass "partially" between terminals as it is shown by the "*current induced by an electron jump over $\lambda_{coll} < L$*". We refer to the integral appearing in **Figure 1** where the *Quantum of charge* appears multiplied by a ratio λ_{coll}/L (usually $\lambda_{coll}/L \ll 1$) that can take any continuous value. This means that we could obtain currents carrying fractions of q in the external circuit. Replacing the Ammeter A_m of **Figure 1** by a capacitance C_{Meas} we would have the first capacitor (to our knowledge) where the charge appearing on its plates would be any fraction of q. Moreover, we do not need to connect C_{Meas} because *C already is* replacing the Ammeter if we leave the 2TD of **Figure 1** under open circuit conditions.

To say it bluntly: accepting the collision model of **Figure 1** we are renouncing to the quantization of electrical charge. Although the circuits of **Figure 2** allow us to solve accurately noise problems for resistors in TE, let us show below that they are the origin of the above conflict because the lonely resistance R of **Figure 2** is not a complete representation of a noiseless resistor.

The Admittance $Y(jf)$ (measured in A/V or Ω^{-1}) of the circuit of **Figure 2** is:

$$Y(jf) = G + j_B = \frac{1}{R} + j_0 = (G + j_0) \quad (4)$$

where f is the measuring frequency and j is the imaginary unit that multiplies a null Susceptance $B(jf) = 0$ because there are not reactive elements in this circuit. Neglecting edge effects due to the 1-D treatment at hand, the $Y(jf)$ of a device with the geometry of **Figure 1** will be [8,9]:

$$Y(jf) = \frac{1}{R} + j2\pi f \frac{\tau_d}{R} = (G + j2\pi f G\tau_d) \quad (5)$$

Comparing Equations (4) and (5) we observe that the lonely R of **Figure 2** can not represent the dielectric properties of the 2TD of **Figure 1** whose plates D-D clad a volume of non null permittivity $\varepsilon \neq 0$, thus requiring a capacitance C_d in parallel with R. Although this $C_d = \tau_d/R$ was found from Thermodynamics [9], the Complex Impedance that appears repeatedly in [5] means that Quantum Physics also demands a complex Admittance to describe noisy devices. Hence, none of the circuits of **Figure 2** are Quantum representations of the noisy resistor of **Figure 1** because they do not allow for the existence of *Fluctuations* of electrical energy in the 2TD of **Figure 1**. This is why we need the circuit of **Figure 3** to have a Physical model for resistors and capacitors [4-6,8,9].

Another objection to the collision model is the non null time it assumes for electrons travelling between terminals of the 2TD after a series of collisions. We mean that an electron emitted from one of the terminals arrives in the other terminal at a latter time $\Delta t_{transit}$, after many collisions with the matter between terminals. Unaware of C, this is the only option for electrons to pass between terminals and to account for the conduction current in 2TDs. However, C is a much easier and faster path for this purpose. By a Fluctuation of electric field in C an electron will jump instantaneously the whole length L of **Figure 1** (recall the *simultaneous* Fluctuations of charge in the plates of C) and although a mean collision path $\lambda_{coll} \approx 1$ µm hardly would suggest such a jump for $L \approx 1$ cm in **Figure 1**, the existence of C makes believable (and likely) these jumps that we called TAs. The Cause-Effect link between noise currents $i_Q(t)$ and $i_P(t)$ in the circuit of **Figure 3** [4,6] strongly suggests that electrons use C to pass between the terminals of a 2TD.

When a TA occurs the electron that has passed between terminals of the 2TD sets an energy $\Delta E = q^2/(2C)$ J in $t = 0$. This is the way Transducer#1 converts kinetic energy

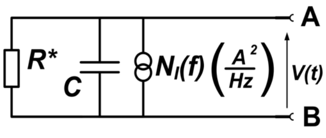

Figure 3. Electrical circuit giving a cogent representation of noisy devices like resistors or capacitors with the shape of Figure 1 [4].

of carriers into a Fluctuation of electrical energy (Cause) subsequently Dissipated (Effect) [4]. Once this energy is in C, it starts to relax by a slower conduction current linked with R that Dissipates this Fluctuation ΔE in the 2TD. This is the Device Reaction (DR) [4], where the reuse of the path through C in opposed sense to remove quickly ΔE is avoided by this relaxation itself. The energy $\Delta E(t = 0^+)$ existing in C slightly after the TA born in $t = 0$ will be lower than $q^2/(2C)$. This means that the electron just displaced has not enough energy to jump back through C and the 2TD has to use the slower path that involves R to continue dissipating this $\Delta E(t = 0^+)$. The non null time Δt required to build a TA (see below) means that a 2TD having suffered one, will spend some time Δt before being ready for a new TA no matter its sign. This guarantees $\Delta E(t = 0^+) < q^2/(2C)$ and avoids the "backward jump" of the displaced electron.

Learning from [7], H. Nyquist had to build a device with both dissipative and reactive elements to explain the thermal origin of the noise measured by Johnson [3]. We refer to the Transmission Line (TL) he ended by two "*conductors of pure resistance R*" (sic), likely because he knew well the meaning of Equation (5). The Susceptance of this TL made possible Fluctuations of electrical energy at each f or the Degree of Freedom (DF) he needed to apply Equipartition. It is worth noting that the null $B(jf_0) = 0$ of the tuned TL of [7] at each f or that of an L-C tank at its resonance frequency $f_0 = (LC)^{-1/2}/(2\pi)$ both imply presence of susceptance in the 2TD, *not its absence*. This presence of two susceptances of equal magnitude but opposed sign creates the null disposition of the 2TD to vary its energy content in response to sinusoidal currents at f_0. However, this presence allows for the Fluctuation of energy content in the circuit under δ-like currents like TAs.

The absence of susceptance would make the 2TD totally unable to store electrical energy and hence, unable to show Fluctuations (TAs) of this type of energy. Thus, *the susceptance of a resistor should not be despised to study its noise* as it is done in the circuits of **Figure 2**. A low C value (e.g. $C < 10^{-13}$ F) should not be despised in **Figure 1** because it means that the bandwidth of the 2TD is wide enough so as to accumulate the thermal fluctuation $kT/2$ J from the flat density $S_V = 4kTR$ V^2/Hz [4,6]. Thus, *R is a spectrum shaper to accomplish Equipartion* in C, a novelty that added to the discrete nature of the electrical charge gives a better model for thermal noise than that coming from **Figure 2** [4]. To assume $C = 0$ in **Figure 1** leads to assume naively absence of susceptance in this device and this wrong idea shows the partial interpretation of [7] that we reveal in [4].

This idea about $C = 0$ likely comes from a misunderstanding of Susceptance as the ability of circuits to store electrical energy. Looking for its true meaning one finds that the *reactive power* $p_C(t)$ in C under sinusoidal regime is equal to the time derivative of its electrical energy: see Equation (7) in Appendix II of [4]. This change with time of the energy in C is proportional to its Susceptance $B = 2\pi fC$. Therefore, $B(f)$ reflects the *ability of the circuit to vary its content of electrical energy*, not its ability to store this energy that, of course, the circuit also has due to its susceptances.

Applying Equipartition in **Figure 3** we obtain:

$$\frac{kT}{2} = \left\langle \frac{Cv^2}{2} \right\rangle = \frac{C\left\langle v^2 \right\rangle}{2} \Rightarrow \left\langle v^2 \right\rangle = \frac{kT}{C} \qquad (6)$$

This is the kT/C noise of a capacitor of capacitance C in TE (≈64 μV_{rms} for C = 1 pF at room T) that is kept in TE by a charge noise in C of mean power $N_1 = 4kT/R^*$ C^2/s that being truly impulsive noise, will have a flat spectral density $N_I(f) = 4kT/R^*$ A^2/Hz where R^* is the small-signal resistance shunting C no matter its origin. This result unifies small-signal resistances with "ohmic" ones found in devices with the shape of **Figure 1**, *but it also discretizes electrical Resistance* into a *random series in time of chances to Dissipate* packets of energy set by previous *Fluctuations*. Since the Phase Noise of *L*-*C* oscillators requires considering R as a *similar series of chances to Convert into heat packets of energy* loaded from the voltage existing between terminals of a 2TD [10,11], let us show the new conduction model that allows for the existence of these two series of Dissipations and Conversions of electrical energy that can occur in 2TDs and that the collision model is totally unaware of.

3. The Reactive Behaviour of Carriers

Used to a microscopic view of Ohm's law based on the collision model, we had to review the conduction mechanism under this model we believed in some time ago. Due to its availability, the aforesaid view about Ohm's law has been taken from [12], where it is written: "*When electric current in a material is proportional to the voltage across it*, *the material is said to be* "*ohmic*", *or to obey Ohm*'*s law. A microscopic view suggests that this proportionality comes from the fact that an applied electric field superimposes a small drift velocity on the free electrons in a metal. For ordinary currents*, *this drift velocity is on the order of millimeters per second in contrast to the speeds of the electrons themselves which are on the order of a million meters per second*. *Even the electron speeds are themselves small compared to the speed of transmission of an electrical signal down a wire*, *which is on the order of the speed of light*, 300 *million meters per second*."

Let us begin this review by recalling again that electrical current never is measured in materials but in devices whose key role in measurements will appear soon. Fixing this misconception we have: "*When electric current in a* 2*TD is proportional to the voltage across it, the* 2*TD is said to be* "*ohmic*", *or to obey Ohm*'*s law* ...." Now, let us consider that the passage of electrons in a 2TD has to be done *independently one of each other* because these quanta of electric charge do not travel side by side merging their charge. Cladding by two ideal plates A and B of $\sigma \rightarrow \infty$ a slice of copper wire of thickness L, we would have a 2TD where a DC current $I_D \approx 1.6$ A would require the independent passage of 10^{19} electrons per second. Each passage would need a fluctuation of electric field that should be created in a time interval Δt shorter than 10^{-19} seconds to avoid time overlapping of these passages that would invalidate their independence in time. In this 2TD we find its capacitance C between terminals A and B at distance L that would be shunted by the conductance G of the copper disk. Each electron displaced from plate A to plate B would set a charge $+q$ C in plate A and $-q$ C in plate B, thus building a System0 of energy $\Delta E = q^2/(2C)$ in Δt. Although the passage of the electron between plates is instantaneous, the energy ΔE it requires *needs time to appear* in the 2TD accordingly to Quantum Physics. This leads to a finite interaction power that avoids a paradox appearing when an infinite interaction power as that of perfectly-elastic collisions in Brownian motion is assumed [6].

The highest ΔE of each System0 built in this 2TD will correspond to its *lowest* capacitance C_∞ coming from plates A and B cladding vacuum of permittivity ε_0. This is: $C_\infty = \varepsilon_0 (A_{Dev}/L)$ F, where A_{Dev} is the area of each plate, because *polarization mechanisms of the copper have no time to react in this instantaneous passage* of an electron between plates. Once System0 with energy $\Delta E = q^2/(2C_\infty)$ J has been created, the 2TD will start to evolve in time (e.g. by redistributing its charges at a speed governed by the τ_d of copper, likely very short). But if System0 can not be created within $\Delta t < 10^{-19}$ s, this electron passage will not take place. For copper wire of ϕ = 1 mm we would have: $A_{Dev} \approx 0.008$ cm^2 and using L = 0.4 mm to have a "slice" suitable for the 1-D treatment at hand, we would obtain: $(A_{Dev}/L) = 0.2$ cm. The energy to be built in C in a time interval $\Delta t < 10^{-19}$ s is: $\Delta E = q^2 L/(2\varepsilon_0 A_{Dev}) \approx 7\times 10^{-27}$ J.

The Time-Energy Uncertainty Principle (TEUP) of Quantum Physics states that a state that only exists for a short time Δt cannot have an energy defined better than $\Delta E_Q \ge h/(4\pi\Delta t)$. Taking the entire time slot $\Delta t \approx 10^{-19}$ s as an upper limit for the existence of each System0, we find that its energy can be defined down to: $\Delta E_Q = 5.27 \times 10^{-16}$ J that roughly is 10^{11} times ΔE. Thus, the familiar copper wire made from slices like this one is a 2TD that needs much more time than Δt to define each energy state required by the independent passage of 10^{19} electrons per second. Hence, a conduction current $I_D = 1.6$ A in copper wire coming from the independent passage of electrons between terminals would infringe Quantum Physics. This is why *nobody has observed the shot noise of this passage of electrons* that would be a flat density $S_{NotSeen} = 2qI_D$ A^2/Hz from DC ($f \rightarrow 0$) up to $f_{NS} \approx 1/\Delta t$ that should be observed routinely. The suspicious $f_{NS} \approx 10^7$ THz surpassing largely the Quantum limit f_Q ($f_{NS} \approx 10^6 \cdot f_Q$) and $\Delta E_Q \gg \Delta E$ infringing Quantum rules explain this absence of $S_{NotSeen}$ and not Equation (1), where the conversion of the $2qI$ A^2/Hz noise density into V^2/Hz by the square of the noiseless resistance r_d [4] is wrong if we consider the unavoidable C of each differential diode.

The above result comes from a "well known" property of electrons that is their mutual interaction bringing them to the surfaces of a conductor or preventing them from travelling together as bigger quanta of charge. Thus, the net passage of electrons between terminals of a 2TD can not account for its conduction currents and the carrier drift associated with the collision model is doubtful because it is based on this net passage. With regard the simultaneous but slow passage of several electrons between terminals of a 2TD that the collision model suggests, it is linked with the unlike existence of the gas of charged particles in the conducting volume of a 2TD without "exploding" towards its surface, as this model assumes.

To find an alternative to carrier drift, let us review some ideas on electron motion in the circuit of **Figure 4**, where C comes from a parallel-plate capacitor with a material between plates whose Resistance is R_X. Since this material can not block the passage of electrons because it is clad between the plates of C, an AC current $i(t)$ will exist in this circuit and its active power on R_X will heat-up it by Joule effect. This series equivalent of the parallel circuit of **Figure 3** is used *to focus our attention on the discreteness of the current* $i(t)$ due to electrons that cross C, but that do not need to cross R_X because C and R_X actually are in parallel as it is shown in **Figure 3**. To see why this passage through $R_X = R^*$ is unnecessary, a good starting point is to realize that $p_R(t)$ (the active power on R_X) only is energy taken from the generator $v_g(t)$ at the rate of $p_R(t)$ J/s or W. Silencing $v_g(t)$ by making $v_g(t) = 0$ and activating the Norton generator between terminals A and B, the energy delivered by this generator at this $p_R(t)$ could be seen as energy converted into heat by an internal loss mechanism between plates of C (represented by R^*) that was activated by making $R_X = 0\ \Omega$ in **Figure 4**.

Readers used to Thèvenin-Norton equivalents could believe that we are replacing the series circuit of **Figure 4** by its Norton equivalent having a resistance R^* in parallel with C. However, we do not want to replace R_X by this R^* suggesting again an electron drift through R^* to account for $p_R(t)$. Contrarily, we think on the way Resistance is accurately emulated by switching the energy that enters and exits a Capacitance [13] as it is shown in **Figure 5**, where the voltage V_0 that would be in parallel with the noise generator $N_I(f)$ of **Figure 3** only means that there is a DC voltage between terminals, that is static or constant on average to simplify. By switching the small capacitance C_f at an enormous rate λ (e.g. $\lambda > 10^{13}$ s^{-1}) we would obtain a "fine-grain" emulation of the resistance R^* not only for the DC or static voltage V_0, but also for cuasi static $V_0(t)$ oscillating up to frequencies well in the GHz range. The reason for this emulation will be clear later.

Recalling what we wrote in previous Section to discard currents carrying fractions of q in the Ammeter of **Figure 1** (e.g. through its C) we can say that any noise current in a 2TD will be discrete. This applies to the currents associated with $N_I(f) = 4kT/R^*$ A^2/Hz in **Figure 3**, which represents a 2TD with the shape of **Figure 1**. For reactive currents $i_Q(t)$ in the 2TD this is clear because *they mean the passage* of discrete electrons between terminals. Concerning conduction current $i_P(t)$, **Figure 4** suggests that conduction current in R_X *will be discrete too* because it has to come from an integer multiple of q crossing C in this series connection. However, the switching mechanism we have advanced will allow for a discrete conduction current without electrons crossing the 2TD on average.

Since **Figures 3** and **4** are equivalent for $v_g = 4kTR^*$ V^2/Hz and $R_X = R^*$ (this is why the plates of C in **Figure 4** have letters A and B of **Figure 3**), any *noise current in resistors is discrete due to its* $C \neq 0$ and the "*current induced by an electron jump over* $\lambda < L$" shown in **Figure 1** that leads to Equation (2) has no Physical sense under

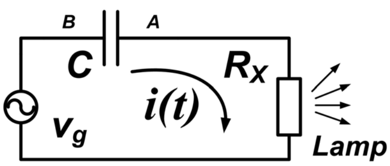

Figure 4. Electrical circuit where *i*(*t*) is discrete due to the discrete nature of the electrical charge that crosses C.

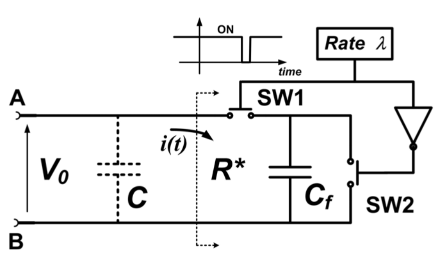

Figure 5. Circuit representing the switching mechanism due to fluctuations of the electric field in a resistor that leads to the current *i*(*t*) in phase with the voltage between its terminals by charging/discharging the capacitance C_f.

the new model of **Figure 3**. This discreteness of $i(t)$ coming from the finite L of a 2TD shows the key role of the device in the measurements we can take. Because the two options for an electron in a 2TD with the geometry of **Figure 1** (e.g. to *jump the whole L through C or not jump at all*) strongly recall displacement and conduction currents as orthogonal processes in a 2TD [4], let us take a closer look to the 2TD of finite L represented by **Figure 3** that is a resistor of resistance R^* shunted by C or a capacitor of capacitance C shunted by R^*.

The name depends on the working frequency f through its Quality factor $Q = 2\pi fCR^*$: good capacitor for $Q \gg 1$ and good resistor for $Q \ll 1$ because $Q = 0$ and $Q \rightarrow \infty$ do not correspond to physical devices [8]. When a voltage $\Delta v = +q/C$ V (Effect) appears suddenly between terminals A and B of **Figure 3**, we can say that its Cause is the instantaneous displacement of one electron from plate A to plate B. This motion of charge in $\Delta t_{TA} \rightarrow 0$ suggests a short and intense current pulse of amplitude $\Delta I = q/\Delta t_{TA}$ carrying the charge: $\Delta t_{TA} \times \Delta I = q$ C. If Δt_{TA} was null, the $+90^\circ$ phase advance of each sinusoidal component of $i(t)$ through C respect to its voltage $v_c(t)$ on C at each f would make null the active power during this instantaneous pulse [6]. The jump of the electron "through R^*" as a possible cause for Δv is discarded because this path where $i(t)$ and $v_c(t)$ are in-phase at each *f needs time to take place* in order to keep finite the interaction power [6] (e.g. $(\Delta i)^2 \times R^* \rightarrow \infty$ when it takes place in $\Delta t \rightarrow 0$).

Hence, the passage of electrons between terminals of a 2TD is easy and instantaneous "through" C, but their passage through the R^* of the 2TD is more difficult. This is easy to accept from the Quantum compliant model of **Figure 3**, but *hard to accept from the collision model with* $\lambda_{coll} \ll L$ typically. In this case, the sudden passage of an electron between terminals of a 2TD becomes believable if it is done by a fast *fluctuation* E_{FL} *of the electric field* in its solid Matter giving a *Fluctuation of* $q^2/(2C)$ J in the electrostatic energy stored along L (e.g. stored in the C that the collision model of Equation (2) is unaware of). Since the Δv due to this field fluctuation E_{FL} and that due to the jump of an electron between terminals is undistinguishable, let us believe in electrons jumping any distance L between contacts by Fluctuations of the electrical energy stored in the C of a 2TD that we called TAs [4,6].

This replacement of charge motion in space by an electric field that varies in time paves the way to explain conduction currents in 2TDs without drifting carriers. As we showed in [4], the rate λ of TAs in the device (resistor or capacitor) of **Figure 3** at temperature T is:

$$\lambda = \frac{2kT}{q^2 R^*} \Rightarrow 2q(\lambda q) = \frac{4kT}{R^*} = S_{Ishot}(f) \qquad (7)$$

thus showing that the familiar Nyquist noise S_I assigned to the resistance R of a resistor simply is the shot noise density $S_{Ishot}(f)$ of the λ fluctuations of electric field taking place per unit time in its C. Considering that shot noise comes from the independent passage [1] of electrons between contacts of 2TDs, the first measurement of shot noise in resistors already was published 84 years ago [3]. The interaction of this noise with the Admittance of Solid-state resistors disguises this discrete shot noise as a continuous Johnson noise coming from the huge rate λ ($\lambda \approx 3 \times 10^{14}$ s^{-1} for 1 kΩ at room T) by which small voltage steps ($\Delta v \approx 0.16$ µV for $C = 1$ pF), each decaying with time constant $\tau_{EN} = R^*C$, create Johnson noise. From **Figure 3**, the active power p_R that enters a resistor will be its mean square voltage noise given by Equation (6) divided by its R:

$$p_R = \frac{kT}{R^*C} = \frac{\frac{kT}{2}}{\tau_U} = \frac{U_{DF}}{\tau_U} \qquad (8)$$

This noise power p_R W, which is the ratio between thermal energy per Degree of Freedom U_{DF} and lifetime $\tau_U = R^*C/2$ of the *energy* in C, is thus *Dissipated* by the resistor in TE at T [4]. For a resistor of $R = 1$ MΩ with $C = 0.1$ pF between terminals we have $\tau_{EN} = R^*C = 100$ ns, thus: $p_R \approx 4 \times 10^{-14}$ W at $T = 300$ K. The spectrum of this noise coming from the Quantum model of **Figure 3** is *formally* equal to Equation (2) by replacing τ_{coll} by τ_{EN}, but they have nothing to do. The Brownian motion ensemble for particles of mass m^* colliding with the lattice that gives the Lorentzian spectrum of Equation (2), is not Nyquist result concerning current fluctuations $S_I(f)$ (A^2/Hz) as we have written previously. This is not surprising because the cut-off frequency f_c of Equation (2) comes from a relaxation of kinetic energy in a gas of charged particles that to exist in the volume of material has to infringe the meaning of its τ_d, whereas the quantum limit f_Q has more to do with Fluctuation Dissipation processes [5] or TA-DR pairs [4] giving electrical noise.

Hence, the Brownian motion ensemble that really matters for electrical noise is shown in **Figure 3** [4,6] because this noise is born from *interactions* of quanta of charge q with the Admittance of the 2TD, or if we prefer: from "collisions" of these quanta in the C of the 2TD with a mean power $4kT/R^*$ C^2/s [4]. The use of this electrical ensemble allows for the separation of *Dissipations* of electrical energy stored in C from *Conversions into heat* of electrical energy that the voltage V_0 stores in a different Degree of Freedom than that of C. Due to the wrong ensemble leading to Equation (2), these two concepts do not appear in the collision model.

Following [4] p_R is an active power, thus electrical energy entering the 2TD that generates heat at p_R W that is delivered to the resistor. However, T does not rise because this p_R comes from previous conversions of kinetic energy of the carriers into electrical one performed by C (Transducer#1). Since this extraction process borrows kinetic energy at the rate of λ TAs per second of $q^2/(2C)$ J each, it cools the resistor at a rate of $\lambda q^2/(2C)$ J/s that from Equation (7) is p_R W too. Therefore, the λ DRs per second observed as Johnson noise dissipating p_R W in a resistor simply are giving-back to this 2TD the energy that its C is borrowing at the same rate on average. This way, a null net transfer of energy results, T does not vary as it must be in TE, and the noise kT/C V^2 on C shows that Equipartition applies to the DF associated to C.

Hence, *Dissipation of electrical energy* in TE that is linked with electrical noise must be different from *Conversion of electrical energy into heat* linked with Joule Effect out of TE. Accordingly to [4], the Dissipation of the energy set by a TA is done subsequently by a DR that involves a slower conduction current governed by τ_d or by $\tau_{EN} = RC$ if the resistor has stray capacitance C_{stray} added to its C_d, see Figure 10 of [4]. To show what we mean, let us consider a macroscopic resistor of $R = 1$ MΩ in TE at $T = 300$ K with $C = 0.1$ pF, thus Dissipating $p_R \approx 4 \times 10^{-14}$ W. This C that is taken as typical for resistors in good setups for noise measurements would include the usually smaller C_d offered by typical conductors with τ_d below the ns. Biasing this resistor by a DC current $I_{DC} = 2$ μA the active power $p_{DC} = 4$ μW entering this 2TD would not rise very much its $T \approx 300$ K. Thus, the Johnson noise of this resistor in TE and out of TE will be similar. From the $p_{DC}/p_R = 10^8$ factor between the active power the resistor handles in each case, the way the active power p_R is *Dissipated in TE* can not be the way the active power p_{DC} is *Converted into heat out of TE* as we had to consider from the behaviour of the Phase Noise known as Line Broadening in *L-C* oscillators [10,11].

Figure 6 allows to show the conduction mechanism that keeping the λ TAs per second of the resistor in TE (thus its noise power p_R), is capable to convert into heat its $p_{DC} = 10^8 \cdot p_R$. Since each TA is a field fluctuation linked with current *in-quadrature* with the voltage of the 2TD in sinusoidal regime, a good way to keep undisturbed the rate λ of Equation (7) is to focus on a current that always is measured *in-phase* with $v(t)$. We mean the DC current under the static field between terminals linked with a DC voltage term V_0 in the $v(t)$ of a resistor. Because no new displacements of charge other than those of TE can take place in the resistor under $V_0 \neq 0$, let us consider dipolar structures of charge that *polarized by the electric field* V_0/L (V/cm) will load electrical energy from this static V_0 between terminals. This type of reaction is well known as a static process of dielectrics that is unable to sustain a constant current in time. But when this process becomes discontinuous as it happens with the carriers of a 2TD, it allows for the conversion of electrical energy into heat at the rate $p_{DC} = V_0^2/R^*$ that Joule Effect requires in **Figure 3**.

Figure 6 shows the Conduction Band (CB) diagrams of a Metal-Semiconductor-Metal (MSM) resistor made from two ohmic contacts or plates, see **Figure 1**, cladding a volume of n-type Semiconductor whose *carriers* are *free electrons* in the CB. Sketched in **Figure 6** also are the *dipolar charge densities* (in C/cm^3) linked with an electron in a quantum state (QS) of the CB. The negative charge $-q$ of this carrier has a wavefunction distributed in the volume of this 2TD seeking to screen a fixed $+q$ charge also distributed in this volume to minimize electrostatic energy. This distributed dipole of charge contributes to the charge neutrality found in the bulk region of a 2TD. Note that for TAs (e.g. fluctuations of electric field) the two plates of **Figure 6** are connected in such a way that a plate only can emit an electron to a QS of the CB when the other plate captures simultaneously the free electron that was previously in this QS [4].

Emissions without this simultaneous capture will be considered later. **Figure 6** shows two energy spikes that electrons easily cross because those metal atoms of the plates that have diffused to form an n^+-n-n^+ structure, make them very thin. This facilitates electron tunnelling through these barriers (e.g. capture and emission of electrons by the terminals of the 2TD). There are $\lambda/2$ Captures per second and $\lambda/2$ Emissions per second at each plate on average, thus λ TAs per second in the 2TD, 50% of each sign. Used to Emission-Capture processes assigned to the handy carrier traps, the novelty added by C is that each Capture of an electron by one contact implies the simultaneous Emission of an electron from the other. The electric field of C synchronizes these two processes that are fully equivalent to a Fluctuation of $q^2/(2C)$ J in the energy of C that we called TA in [4].

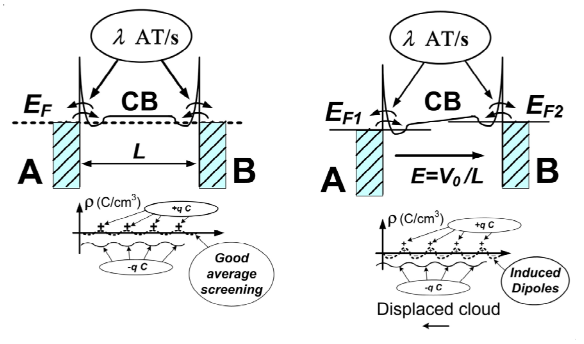

Figure 6. Band diagrams of a resistor made from n-type semiconductor and volumetric densities of charge associated to one of its carriers in two different conditions: (a) In TE; (b) With a static voltage V_0 between terminals (see text).

By symmetry, the average capture rate in each plate is $\lambda/2$ and when an electron of the CB is captured by one terminal, the extended *wavefunction of its –q charge collapses into a wavefunction that localizes this charge* on the surface of one plate (e.g. a TA takes place). Hence, those electrons forming carriers in the 2TD *have two DF to attend*: 1) being a long-range dipole between plates in each field fluctuation called TA, and 2) becoming a short-range, distributed dipole, in the volume of the 2TD (e.g. being a carrier in the CB). To attend these two DFs, *the electron will switch in time between these states.*

Concerning emissions of electrons to an empty QS of the CB without a simultaneous capture by other plate, we will say that this "lonely emission" is typical from local defects as impurities for example. In this case the electron arriving in the QS keeps an electrical link with the defect it leaves, thus being liable to be captured at a later time without needing a third element. This way, the electron and the charged defect become the charges $-q$ and $+q$ linked by the electric field in a *new device* liable to give fluctuations in carrier flux, carrier number or in its mobility for example. Since this situation that recalls the electrical coupling between the filament of a vacuum tube and its surrounding electron cloud [14], has been studied recently to explain the flicker noise of electron fluxes in vacuum devices [8], we will not consider here this type of fluctuations that depart from the Fluctuations handled in [4-6].

Because V_0 does not modify noticeably in **Figure 6** the high field of the energy barriers, the contact resistances entering in the whole resistance R^* of the resistor do not vary and this keeps λ, see Equation (7). This way, V_0 or its current in-phase I_{DC} do not change the rate λ of TAs and the Johnson noise of the device under V_0 is similar to that in TE. By loading energy on each carrier that was proportional to $(V_0)^2$ and that was *released as heat each time the free electron passed to form a TA*, there would be a conversion of electrical energy into heat at a rate proportional to $\lambda(V_0)^2$. This means an active power proportional to $(V_0)^2/R^*$. Using Equation (7) to make it equal to the active power assigned to Joule effect, the energy U_f that each carrier would load from V_0 would be [10]:

$$P_{DC} = \frac{V_0^2}{R} = \lambda \times U_f \Rightarrow U_f = \frac{q^2 V_0^2}{2kT} = \frac{1}{2} \times \frac{q}{V_T} \times V_0^2 = \frac{1}{2} \times C_f \times V_0^2 \quad (9)$$

Thus, the reaction of each carrier as a small capacitance $C_f = q^2/(kT)$ F *loading energy from* V_0 and releasing it as heat each time it takes place in a TA, allows for the explanation of Joule effect without requiring carrier drift and without changing the thermal noise the resistor had in TE. Thermal activity sustaining in time an imperfect screening between the charges $+q$ and $-q$ of each carrier would make it a thermal dipole of charges $+q$ *and* $-q$ on its plates liable to be polarized. This way, the electric field V_0/L would see these carriers as trembling *dipoles of charges* $+q$ *and* $-q$, each acting as an average capacitance C_f, that would become polarized as sketched in **Figure 6**. Thus, each carrier in the CB would be formed by a *flabby cloud of charge –q distributed* in the volume of the 2TD, aiming at screening as much as possible its portion of charge $+q$ that would be *a sort of rigid density of charge* also distributed within this volume.

Although the exact form of these charge densities sketched in **Figure 6(a)** would depend on lattice atoms, doping, dislocations, etc. and on the Bloch functions defining the wavefunction of each electron within the device, this shape is irrelevant here. What matters is to realize that *carriers* (free electrons in the CB) *are not unipolar charges liable to drift under* the electric field due to V_0 as point charges that, being negatively charged, would "explode" towards the surface. On the contrary, a free electron in the CB is *captive in the bulk* of the 2TD that hides its charge by the aforesaid screening required by charge neutrality. From time to time, this captive dipole will show its charges on the surfaces (plates) of the 2TD. This will occur, each time its electron takes place in a TA or Fluctuation of electric field in the 2TD. This way, the electron continues captive in the 2TD, but looking freer in another Degree of Freedom less subjected to the rigorous law of charge neutrality prevailing in the bulk.

Polarization loading U_f on each carrier will be a fast process for conductors (recall the meaning of $\tau_d = \varepsilon/\sigma$) and since the support of U_f in the volume of the device will disappear each time the carrier appears on the plates in a TA, this U_f will be released as phonons to the volume of the 2TD. This release will be accomplished by the *synchronous shaking of the lattice* at different positions (e.g. those shown by a small cross in **Figure 6**) taking place each time the flabby cloud *exerting force on these points* disappears in the TA. In summary: the release of the energy U_f loaded by a carrier from V_0/L in a resistor *is triggered by each Fluctuation of this field that implicates this carrier*. This replaces drifting charges by interacting fields and explains how to convert electrical energy into heat without carriers drifting in Solid Matter.

Although a TA occurs instantaneously, its associated energy requires some time Δt_{TA} to appear in the 2TD to keep finite the power of this Fluctuation (see a paradox appearing when one uses naively an infinite interaction power [6]). To consider the non null Δt_{TA} that a carrier needs to carry out the TA in which it is implicated, let us use the same TEUP we used to discard carrier drift. Recalling the meaning of System 0, the minimum time interval Δt_{TA} required to define the energy $\Delta E = q^2/(2C)$ of the System0 for each TA would be:

$$\Delta E \times \Delta t_{\text{TA}} \geq \frac{\hbar}{2} \Rightarrow \Delta t_{\text{TA}} \geq \frac{\hbar}{q^2} \times C = R_K \times C \quad (10)$$

where R_K is link with the Quantum Hall Resistance we found in [15] looking for a metrological interest of the discrete resistance proposed in [4]. Before reading [15] we considered R_K as the *lowest possible resistance per carrier* of a 2TD giving the maximum active power per carrier in it. This appears by considering the highest rate of TAs in a 2TD with only one carrier that would be: $\lambda_Q = 1/\Delta t_{\text{TA}}$ s^{-1} if the ΔE set in C by each TA disappeared instantaneously. Since a TA is the Cause that sets $\Delta v = q/C$ V in the 2TD (Effect) we can take Δv as the average voltage in C during Δt_{TA}. If the energy ΔE was removed by the arrival of the next TA, the active power sustaining in time the static voltage Δv in C would be:

$$P_Q = \lambda_Q \times \frac{q^2}{2C} = \frac{q^2}{\hbar C} \times \frac{q^2}{2C} = \frac{(\Delta v)^2}{2R_K} \quad (11)$$

Equation (11) means that P_Q is the active power that enters the Conductance $G_Q = 1/(2R_K)$ driven by the continuous voltage Δv sustained in this way. Thus, G_Q would be the highest Conductance of a 2TD like that of **Figure 1** with only one carrier in its volume, due to the maximum rate of TAs in its capacitance C. However, **Figure 7(a)** shows the *outer capacitance C* of this 2TD due to charge densities induced by each TA on the external faces of its plates of $\sigma \rightarrow \infty$ under the open-circuit condition that exists for an instantaneous TA due to the inductance of external wires. In the 1-D model at hand, the magnitude of electric field at points **a**, **b**, **b'** and **a'** of **Figure 7(a)** is the same because the charge density on each surface has the same magnitude. Since the plates are equipotential, the voltage drop going from point **a** on plate A to point **b** on plate B will be equal to the voltage drop going from point **b'** to point **a'** on the outer surfaces. Hence, each TA sets ΔE in the inner C and ΔE in the outer C, thus $\Delta E_{True} = q^2/C$ J in all, which is the energy of two parallel sheets of charges $+q$ *and* $-q$ separated by a distance L. This is the "electrical image of a TA" that appears in **Figure 7(b)** together with its fluctuation of electric field $E_{FL} = q/(\varepsilon_0 A_{Dev})$.

Using ΔE_{True} in Equations (10) and (11) the active power needed to sustain the static voltage Δv in C becomes: $p_{true} = 4p_Q$. Connecting a generator to this 2TD, the outer C of **Figure 7(a)** becomes the capacitance of the new 2TD that the generator is. Given the opposed signs of reactive currents in the inner and outer C from the generator viewpoint, this generator would be delivering an active power $p_{true} = 4p_Q$ while absorbing $2p_Q$ due to its role as inner C. Therefore, this generator would be delivering an active power $P_{meas} = 2p_Q$ W to sustain Δv. Thus, the lowest resistance per carrier that a 2TD can offer is R_K.

Equipartition theorem also must apply to the DF that C_f represents. For an electron emitted to the lowest energy level of the CB, the first image of its dipolar charge would show its $-q$ cloud closely wrapped around its $+q$ array, good average screening of **Figure 6(a)**. This is a very cold carrier that interacting thermally will pass to show the mean thermal energy $kT/2$ J in TE by *an imperfect screening between its* $+q$ *and* $-q$ *charges* varying randomly with time around its minimum value. Viewing this trembling dipole as two charges $+q$ and $-q$ separated by a distance $d(t)$ varying with time, each carrier is thus a capacitance $C_F(t)$ of mean value $\langle C_F(t)\rangle$ "built" by the average energy $kT/2$ J set by Equipartition in this DF linked with carrier polarization. Therefore, $C_F(t)$ should fluctuate around this mean value $\langle C_F(t)\rangle$:

$$\frac{kT}{2} = \left\langle \frac{q^2}{2C_F(t)} \right\rangle = \frac{q^2}{2\langle C_F(t)\rangle} \Rightarrow \langle C_F \rangle = \frac{q^2}{kT} = \frac{q}{V_T} = C_f \quad (12)$$

Hence, the mean capacitance $\langle C_F(t)\rangle$ set by Equipartition for each carrier in TE is the C_f that Equation (9) needs to account for Joule Effect out of TE by carrier polarization. Loading energy from V_0 in C_f and releasing it to the lattice as heat each time a TA takes place, the active power $p_{DC} \gg p_R$ is converted into heat without requiring carriers colliding within the 2TD. Since this p_{DC} will try to heat-up the resistor out of TE due to its $V_0 \neq 0$, we are assuming a good extraction of this heat to keep T close to its value for $V_0 = 0$ in order to keep its noise of TE. This new model for the familiar Joule effect departs markedly from the one we had accordingly to the microscopic view of Ohm's law given in [12] that is based on carriers drifting under the action of the field V_0/L.

The deep rooted character of this idea on electrical

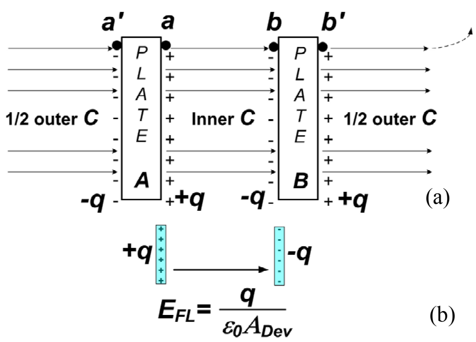

Figure 7. (a) 1-D sketch of electric field and charge densities associated with a thermal action in a 2TD having two idealized terminals (see text); (b) 1-D sketch of electric field and dipolar charge associated with a fluctuation of electric field E_{FL} taking place in a real 2TD (e.g. a thermal action).

conduction requiring "*carrier motion in space*" can be seen in Section 2.3 of [16] by these phrases:

"*The basic physical fact to be borne in mind when discussing polarisation is that polarisation arises from a finite displacement of charges in a steady electric field and this is to be contrasted with the complementary physical phenomenon of electrical conduction which is characterised by the fact that conduction arises from a finite average velocity of motion of charges in a steady electric field*." After these sentences, we also can read this one about polarising species "*...which are incapable of leading to a continuing conduction current in a static field*" [16] (except for enormous fields ≈ 10^{10} - 10^{11} V/m breaking dipoles that we will not consider here).

Working with noise, "*static*" is more the exception than the rule and switching mechanisms making devices work are familiar. Transformers unable to work under a static or DC voltage V_0, perform well if the voltage V_0 is switched in time and a capacitance C_f that is charged and discharged at a high rate λ can emulate very convincingly a Resistance R^* by the conversion of electrical power into heat that takes place in **Figure 5**, where the active power p_{DC} leaving the generator V_0 towards its *switched emulator* of R^*, simply is λ times the energy loaded in C_f: $p_{DC} = \lambda C(V_0)^2/2$ J/s or W. To emulate R^* = 1 kΩ by the small capacitance C_f of a single carrier in the resistor of **Figure 5** at T = 300 K, the required rate is given by Equation (7): $\lambda \approx 3 \times 10^{14}$ commutations per second. This is a high rate that could conflict with the TEUP, but dividing λ by the huge number of carriers (parallel channels) that exist in typical 2TDs, no conflict appears.

With $\lambda \approx 3 \times 10^{14}$ s^{-1}, the active power $p_{DC} = V_0/R^*$ that leaves the generator V_0 in **Figure 5** is exactly equal to the active power converted into heat by a resistor of R^* = 1 kΩ driven by V_0. The inverter of **Figure 5** guarantees *two excluding states* for switches SW1 and SW2 emulating the two excluding states of the electron in **Figure 5**: 1) *free carrier* in the volume (SW1 ON, SW2 OFF) or 2) *long range dipole on the terminals* (SW2 ON, SW1 OFF). When SW1 becomes ON, the carrier loads its C_f with $U_f = C_f(V_0)^2/2$ in a time interval $\Delta t_{load} \approx \tau_d$. This U_f remains in C_f until the next TA implicating this electron because this circuit does not have resistances other than R^* emulated in this way. Concerning the way active power leaves R^* we will say that closing briefly SW2 during Δt_{TA} the energy U_f leaves C_f as heat "*in the wire*" of SW2. However, the null resistance of this wire hardly would convert electrical energy into heat at first sight. The problem can be solved by considering this wire as a very low inductance $L_S \to 0$. This would lead to an L-C_f resonant circuit of resonance frequency $f_0 \to \infty$ giving a high enough number of periods during Δt_{TA} so as to radiate all the energy U_f that was in C_f. This way, U_f would leave C_f *converted into a different type of energy*. After the brief Δt_{TA}, SW1 would become ON and C_f would acquire another packet of energy U_f. Repeating the "TA state" (SW1 OFF, SW2 ON) λ times per second, an active power $p_{DC} = (V_0)^2/R^*$ would be converted into photons and radiated by the L-C_f circuit. The "radiation resistance" of this switched L_S-C_f tank would emulate the continuous resistance of $R^* = 2/(\lambda C_f)$ Ω that seems to be connected to the generator V_0 due to the p_{DC} it delivers in an ultrafast switched mode that looks continuous as Ohm's Law considers.

For switching rates like $\lambda \approx 3 \times 10^{14}$ s^{-1} the current $i(t)$ of **Figure 5** looks like DC (e.g. continuous) and if V_0 was a quasi-static voltage of amplitude V_0 oscillating at 100 MHz for example, the current $i(t)$ would track closely V_0 as a sinusoidal current of amplitude V_0/R^* A at 100 MHz that would be "totally" *in-phase with* $V_0(t)$. This would be so because the period T_0 = 10 ns is a time window for 3×10^5 TAs. Due to this huge switching rate the Phase uncertainty would be of the order of $\approx 1/(3\times10^5)$ rad [11]. Unaware of the discreteness of $i(t)$ and unable to measure a relative phase with this degree of accuracy, we would think of this current as the conduction current of electrons drifting through a "continuous" resistor of R^* = 1 kΩ driven by V_0 oscillating at 100 MHz. The novelty is that R^* is *a discrete series of* λ *chances in time to convert electrical energy* into another form. This idea has been used to explain Phase Noise in L-C oscillators [10,11].

The behaviour of carriers as distributed *dipoles* added to their need to appear as *charges* on the terminals of a 2TD from time to time, lead to show that the generation of heat by Joule Effect comes from a *Switched Current* (SC) that looks totally *in phase* with any AC voltage $V_0(t)$ on the 2TD for frequencies $f \ll \lambda$. This limit however, will be lower in general: $f \ll f_{EN}$, due to the cut-off frequency $f_{EN} = 1/(2\pi\tau_{EN})$ of the circuit of **Figure 3**. This lower limit set by the Admitance of the 2TD further disguises this SC as "continuous current" or DC. This recalls the action of this Admittance on the shot noise of TAs disguising them as a continuous Johnson noise. Recalling words about "*the complementary physical phenomenon of electrical conduction*" [16] respect to static polarization, let us say that discrete *charges that cross the* 2*TD as a mean current* $\langle i_Q(t)\rangle$ = I_{DC} in capacitive devices produce its familiar shot noise S_{shot} = $2qI_{DC}$ A^2/Hz whereas *carriers that do not cross* the 2TD are capable however, to emulate a mean current $\langle i_P(t)\rangle$ = I_{DC} in-phase with its voltage $v(t)$ that is noiseless.

Finally let us say that this model explains well why the Phase Noise of an L-C oscillator is reduced as its Signal power rises provided its T raise is low. Unaware about the difference between Dissipation of energy and its Conversion into heat, an increase of the active power (Signal power) in the resonator of an oscillator would increase its Dissipation of energy and thus, its Noise power by the same factor. This way, the Phase Noise would not decrease by increasing the Signal power because the Signal/Noise power ratio would not change either. Hence, the decrease of Phase Noise in *L-C* oscillators as their Signal power rises is an added proof for this conduction model where carriers do not drift either in the resistor embedded in their *L-C* resonators [10,11].

4. Conclusions

Electrical noise and electrical conduction are linked with the electrical voltage measured simultaneously between the two terminals of a device whose capacitance C plays a key role in the origin of this voltage. Due to the discreteness of electric charge, C quantizes the currents in the device so as to produce discrete Fluctuations of electrical energy that are equivalent to the jump of an electron between terminals of C. This defines the thermal action or Fluctuation of electric field in C (E_{FL}) that is the Cause of a subsequent device reaction (Effect) that Dissipates the energy $\Delta E = q^2/(2C)$ J set by the TA.

Carriers in Solid State resistors are distributed dipoles loading electrical energy U_f from the electric field existing in these devices. This U_f is thus stored in the volume of the device, not in C. When a TA takes place, one of these carriers collapses into a long-range dipole between terminals that stores a Fluctuation ΔE in C due to the displaced charge. This ΔE is borrowed from the kinetic energy of the carrier and the energy U_f that was loaded on this carrier is released uniformly as heat to the volume that defines the $G = 1/R$ of the device. Only the energy ΔE stored by each TA in C is Dissipated by the DR that is a relaxation of energy with lifetime $\tau_U = (R^*C)/2$.

The Conversion of electrical energy into heat (Joule Effect) is a process that involves carriers, but it does not require displacement currents other than those that already existed when the 2TD was in TE. If temperature raise is small, this conversion process does not add shot noise to the shot noise that appears disguised as Johnson noise in resistors or as kT/C noise in capacitors. This Conversion of energy into heat that differs from its Dissipation in electrical noise also explains why Phase Noise in *L-C* oscillators decreases as their Signal Power is increased. This model where the classical Resistance is discrete in time shows the capacitive link that exists between this Resistance and the Quantum Resistance $R_K = \hbar/q^2$ that would be the lowest possible resistance per carrier in a two-terminal device.

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