On the Electrical Origin of Flicker Noise in Vacuum Devices

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Abstract—We have recently shown that thermal noise in the space-charge regions of solid-state devices can account for most of their excess noise, whose $1/f$ spectrum is produced by the dc bias that was used to convert resistance noise into a voltage noise to be measured. This spectrum reflects the modulation of an energy barrier that confines carriers along the channel of such devices—a feature that was also found for electrons around cathodes of vacuum tubes. Using this novel theory, we can predict a flicker noise in vacuum tubes—a noise whose origin has eluded scientists since its early report by Johnson in 1925.

Index Terms—Barrier modulation, capacitor noise, flicker noise, floating grid (FG), Lorentzian noise cavity (LNC), shot noise, vacuum device.

I. INTRODUCTION

ORD KELVIN said “To measure is to know,” a sentence is particularly true when electrical noise has to be measured. Due to the unpredictable character of this electrical fluctuation, much care has to be taken to perform measurements that are free of misleading data for its interpretation. After having shown that the $1/f$ resistance noise that was summarized by Hooge’s empirical formula for solid-state devices comes from the imperfect shielding of the channel of these devices [1], we will explain why vacuum tubes show flicker noise with $1/f$-like spectrum. Aside from the control of this noise, which limits the accuracy of precision measurements, this new knowledge can also help in improving instrumentation based on thermoionic electron emitters.

In a paper by Irving Langmuir [2], we found calculations on the location of a plane of minimum potential (PMP) next to a thermoionic emitter that agreed with the idea of a cloud of electrons around the cathode of vacuum tubes that we had seen in old books on electronics. This PMP that comes from an electrostatic coupling between cathode and electrons that were emitted with nonnull initial velocities sets the top of an energy barrier for electrons that limits the plate current $I_P$ that was obtained from the equipotential cathode (EC)-emitting electrons, and therefore, this cloud of negative charge around the cathode is a subtle floating-grid (FG) electrode that exists between the cathode and plate in vacuum diodes. This instance is quite the case when $I_P$ is a space-charge-limited plate current between an equipotential plate (EP) that was biased by a voltage $V_P$ with respect to an EC in front, as studied in [2]. Increasing $V_P$ while keeping the EC at temperature $T_E$ or reducing $T_E$ while keeping $V_P$, the aforementioned PMP can be removed, thus leaving a saturated $I_P$ current that was limited by the electron flux that the EC can emit. Vacuum diodes that work under saturated $I_P$ are good sources of shot noise that has long been used [3], because the aforementioned space-charge cloud in front of the cathode in space-charge-limited tubes acts as a buffer that partly suppresses the fluctuations [4]. To our knowledge, no other role from the noise viewpoint has been reported for such a cloud, but considering that an electrically heated cathode (EHC) is not an EC and that the FG is a gate electrode that was inadvertently left floating like the floating gates that give rise to $1/f$ resistance noise in solid-state devices [1], this paper shows how this novel theory can also explain the flicker noise in vacuum diodes that, despite its early report by Johnson [3], is still under debate.

As shown in [1], the capacitive coupling of solid-state devices with neighbor conductors as a substrate or a shield produces a resistance noise in these devices, which is used to give a $1/f$ spectrum of voltage noise density due to the disturbance of the dc bias used to convert resistance noise into voltage noise. This noise, which theoretically backs Hooge’s empirical formula, not only gives a good reason for the ubiquity of $1/f$ noise in solid-state devices with space-charge regions (SCR) at their boundaries or embedded around dislocations [5] but also answers two questions that we had, ever since we have written our first paper on $1/f$ noise [6]: 1) the reason that the highly dislocated material in [6] was a very efficient $1/f$ noise generator and 2) a personal worry on the role played by the shield that encloses the samples in the noise data that were obtained. Based on the answer of this novel theory to this role, we pass to consider parasitic capacitors in vacuum devices as possible sources of their $1/f$ noise, because the excess noise in solid-state devices was due to the backgating effect of thermal noise that was present in resistance–capacitance circuits or relaxing cells that were still not considered on their main path (channel) for electrical conduction. This channel itself, which is made of some material of dielectric relaxation time $\tau_d$, is a relaxing cell of time constant $\tau_d$ that can have an upper limit for its flat spectrum of thermal noise below the quantum limit given by Nyquist for “conductors of pure resistance $R$” [7]. As pointed out in [1], this quantum limit should not be blindly applied to resistors that cannot offer a pure resistance $R$ without...
a capacitance $C_d = \tau_d/R$ in parallel with $R$. The null dielectric constant of the material needed for resistors that offer $C_d \to 0$ is in conflict with the finite speed that was expected from Einstein’s Special Relativity for the electromagnetic wave in the aforementioned material.

This lack of all-dissipative devices with null-quality factor $Q = 0$ led us to study the feasibility of all-reactive devices with $Q \to \infty$ (thus, capacitors of pure capacitance $C$). Looking for a high-$Q$ capacitor, we found that two metal plates that were separated in vacuum by a distance $d_g$ and kept at some temperature $T > 0$ K cannot offer a pure $C$, because they also give a dynamical resistance $r_d$ shunting $C$ due to the thermoionic emission of electrons from each plate toward the other. This feature, which prevents the existence of capacitors with $Q \to \infty$ at some $T > 0$, led us to consider that systems with two electrostatically coupled “plates” will be relaxing cells or $R$–$C$ parallel circuits that bear a Lorentzian spectrum of electrical noise with finite amplitude and nonnull bandwidth, which agrees with the fact that temperature and thermal equilibrium (TE) apply to systems that exchange energy with the environment in a finite time—an exchange that a pure capacitance $C$ without a finite resistance $R$ in parallel cannot electrically do.

The plates of a capacitor in TE being in TE one with each other must have some relaxation mechanism that gives rise to a dynamical resistance $r_d$ between them, because a finite $r_d$ opens the way for the energy stored in $C$ to relax toward its TE value after having thermally impulsively fluctuated. We mean that any thermal charge fluctuation $\Delta Q$ that takes place in a capacitor of capacitance $C$ has to relax with time. For $r_d \to \infty$, this reaction, by following the impulsive action, would require an infinite time to remove $\Delta Q$ by the null conduction current ($i = \Delta v/r_d \to 0$) driven by the finite voltage step $\Delta v = \Delta Q/C$ that $C$ allows for appearing between plates from the impulse-like displacement current of weight $\Delta Q$. Thus, TE cannot be reached in a pure $C$ without some finite $R$ in parallel, and hence, any capacitor at $T > 0$ will become a relaxing cell or $R$–$C$ parallel circuit that shows thermal noise with a Lorentzian spectrum. Based on this idea, we will predict a $1/f$ electrical noise for vacuum tubes; a noise with units of $A^2$ or $V^2$ that differs from the resistance noise ($\Omega^2$) with $1/f$ spectrum in [1]. Moreover, the consideration of shot noise that drives Lorentzian noise cavities (LNCs), which we have done in this paper, allows us to more precisely state the results in [1] for solid-state devices.

II. ELECTRICAL TUNABILITY OF THE LORENTZIAN NOISE IN THERMOIONIC NOISE CAVITIES

Fig. 1(a) shows a parallel-plate capacitor made of two metallic plates, with each being of area $A_P = W \times L$ and separated by a distance $d_g$ in a vacuum of dielectric constant $\varepsilon$ (F/cm). Neglecting edge effects, the capacitance $C_g$ of this device is

$$C_g = \varepsilon \times \frac{(W \times L)}{d_g} = C_0 \times (W \times L)$$

(1)

where $W$, $L$, and $d_g$ are given in centimeters, and $C_0 = \varepsilon/d_g$ (in F/cm$^2$) is the capacitance per unit area. This capacitor, which is kept at temperature $T$, will show a voltage noise $v_n(t)$ whose mean-square voltage is $\langle (v_n)^2 \rangle = kT/C_g$. This result is the so-called $kT/C$ noise [8] of a capacitor, which is the same regardless of the resistance value $R$ in parallel with $C$ [9]. This striking feature means that $C_g$ sets $\langle (v_n)^2 \rangle$ in the $R_dyn-C_g$ circuit in Fig. 1(b), but the spectrum of $v_n(t)$ (e.g., $S_V(f)$ in $V^2/Hz$) is set by $R_{dyn}$ and $C_g$ together to keep the mean-square voltage $\langle (v_n)^2 \rangle = kT/C_g$ that corresponds to a mean noise power $N = kT/\tau$ on $R_{dyn}$, where $\tau = R_{dyn}C_g$ and $f_0 = 1/2\pi\tau$ are the time constant and cutoff frequency of this relaxing cell.

The aforementioned results give reasons to look for the $R_{dyn}$ that defines the spectrum of $v_n(t)$ in Fig. 1(b), which will be the dynamical resistance of this electrostatic device, because $v_n(t)$ is a small voltage signal. Although $R_{dyn} = (\partial I/\partial v)^{-1}$ for junction diodes is well known, it is not the case for the $R_{dyn}$ that we are looking for, which can be obtained using a thermoionic theory [10] for each electron flux that was emitted from each plate toward the other. To analyze this situation, we will first consider the energy band diagrams, as shown in Figs. 2(a) and 3(a), that exist in TE for electrons, whose thermoionic current densities $J_{S1}$ and $J_{S2}$ will thus be

$$J_{S1} = J_{S2} = J_S = AT^2 \times \exp \left( -\frac{\Phi_G}{kT} \right)$$

(2)

where $A$ is the Richardson constant $(A/cm^2/K^2)$, and $\Phi_G$ is the highest work function of the two metals or electron gases that exist in the “plates.” The two opposed saturation currents $I_1 = I_2$ that travel from one plate to another in TE will be $I_S = J_S \times (W \times L)$, and because $I_1$ and $I_2$ do not instantaneously cancel but only on the average, their noises must be added in power (as uncorrelated noises they are) to obtain the total noise source in the system.

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The total shot noise current density is thus 
\[ S_V(f) = 4qI_S \] 
between terminals due to the filtering action of the \( R_{\text{dyn}} = C_g \) relaxing cell, converting a broadband \( S_V(f) = 4qI_S \) into the narrowband \( S_V(f) \) whose shape is Lorentzian due to the first-order low-pass transfer function of \( Z(j\omega) \), the impedance of \( R_{\text{dyn}} \) and \( C_g \) in parallel. \( Z(j\omega) = R_{\text{dyn}} \) thus produces \( R_{\text{dyn}} \) in \( R_{\text{dyn}}(f) = 4qI_S(R_{\text{dyn}})^2 \) must be the right value of the noise voltage density \( S_V(f) \) that integrated in frequency from \( f \to 0 \) to \( f \to \infty \) gives the mean-square voltage noise \( kT/C_g \) of this relaxing cell in the TE required by thermodynamics [8]. This \( kT/C_g \) noise only appears in the relaxing cell if the low-frequency part of \( S_V(f) = 4qI_S \). To obtain \( R_{\text{dyn}} \), we advance that \( R_{\text{dyn}} \) is \( R_{\text{TE}} = V_T/I_S \), and from \( 4qI_S(R_{\text{dyn}})^2 \), we advance that \( R_{\text{dyn}} \) is the noise spectrum of this relaxing cell. \( C_g \) is the material character of \( R_{\text{dyn}} \). The uncorrelated character of the shot noise in \( I_1 \) and \( I_2 \) allows us to consider that, if one of these currents disappears (e.g., out of TE), the broadband shot noise that drives the cell will be the shot noise of the remaining current. Finally, note that the electron cloud in [2] for each plate that emits the cell will be the shot noise of the remaining current. Finally, our approach, by squeezing the whole electron cloud in a thin FG at distance \( d_g \) from the cathode (exactly at the spatial position of the PMP in [2]), and the actual electron cloud that faces an EC will have similar modulating effects on the flux of emitted electrons that cross the cloud and are collected by an EP that was put to the right of plate \( G \) in Fig. 1. We mean that our simplifying approach for the electrostatic coupling between the cloud of negative charge and the cathode, which was used to study electrical fluctuations in the device, is the first approach to explain its noise without requiring sophisticated models, e.g., methods that involve carrier traps.

Inverting the sign of \( v \), we obtain Fig. 3(b), where the thermoionic flux in the sense \( K \to G \) remains unaffected, whereas the flux in the sense \( K \to G \) is exponentially weakened by the barrier increase in \( qv \) eV thus produced. Thus, \( R_{\text{TE}} \) remains for these negative \( v \) values, and this result means that our system behaves like a solid-state diode whose exponential \( \pm v \) curve allows for obtaining its \( R_{\text{dyn}}(v) \) for small voltage fluctuations as those of electrical noise. Differentiating (4), we have

\[
R_{\text{dyn}}(v) = \left( \frac{\partial I}{\partial v} \right)^{-1} = \frac{V_T}{I_S} \exp \left( -\frac{v}{V_T} \right) = R_{\text{TE}} \exp(-u).
\]

This result states that the \( R_{\text{dyn}}(v) \) of this electrostatic system exponentially varies with \( v \) or that its quiescent bias tunes its voltage noise similar to junction diodes [1], [5]. This result also confirms the \( R_{\text{TE}} = V_T/I_S \) that we advanced from the \( kT/C_g \) noise in TE—an energy approach that states that a mean-square voltage noise \( \langle v_n^2 \rangle = kT/C_g \) in \( C_g \) that was shunted by an “immaterial” \( R_{\text{TE}} \) requires a voltage noise density \( S_{\text{TE}}(f) \) that is equal to the \( S_{\text{TE}}(f) \) of a “material” resistance \( R = R_{\text{TE}} \). Due to this role of \( R_{\text{dyn}} \), we have

\[
S_{\text{TE}}(f) = 4kT R_{\text{TE}} \times \frac{1}{1+(f/f_0)^2} = \frac{2kT}{\pi C_g} \times \frac{(1/f_0)}{1+(f/f_0)^2}.
\]

Thus, a Lorentzian spectrum of cutoff frequency \( f_0 = 1/[\pi R_{\text{TE}} C_g] \), which was integrated from \( f = 0 \) to \( f \to \infty \), gives the right-mean-square noise voltage \( \langle v_n^2 \rangle \), which is an expression equal to the \( \pm v \) curve of a Schottky diode under forward bias up to a forward bias \( v = V_{\text{SAT}} \), where the forward current of this device \( I_{K \to G} \) will saturate to the value \( I_{\text{MAX}} \) limited by the thermoionic emission from the cathode \( K \). Thus, (4) and Figs. 2 and 3 show how the way the plate current \( I_P \) is limited in vacuum diodes by the energy barrier whose top is at distance \( d_g \) from the cathode. Although the linear energy barrier that we use somewhat differs from the rounded barrier from the self-consistent solution in [2] for an EC, the limiting action or \( I_P/I_{\text{MAX}} \) ratio in [2] and that of (4) are similar. Therefore, our approach, by squeezing the whole electron cloud in a thin FG at distance \( d_g \) from the cathode (exactly at the spatial position of the PMP in [2]), and the actual electron cloud that faces an EC will have similar modulating effects on the flux of emitted electrons that cross the cloud and are collected by an EP that was put to the right of plate \( G \) in Fig. 1. We mean that our simplifying approach for the electrostatic coupling between the cloud of negative charge and the cathode, which was used to study electrical fluctuations in the device, is the first approach to explain its noise without requiring sophisticated models, e.g., methods that involve carrier traps.

Electrons that cross \( d_g \ll 1 \) cm with thermal speeds of more than \( 10^8 \) cm/s at \( T \approx 2400 \) K have transit times \( T_\gamma \) that are below the nanosecond. This condition makes the shot noise of this passage of discrete charges a broadband current noise up to frequencies in the gigahertz range whose low-frequency current noise density is \( S_I(f) = 2qI_D (A^2/Hz) \), with \( I_D \) being the density of current carriers in the device.
the mean current value. Thus, $S_I(f)$ is flat up to frequencies
that are well above the $f_0$ that the filtering action of $C_g$ and $R_{\text{dyn}}$ produces in $S_{\text{TE}}(f)$ between plates. Most of the electrons that were emitted by the cathode toward the FG are reflected back; thus, this electrostatically coupled system looks like a cavity with two opposed currents that were formed by short current pulses due to electrons that travel between plates that coexist with two relaxation currents formed by slowly decaying current pulses due to the integrating action of $C_g$ on each short current pulse that converts it into a small voltage step $\Delta v = q/C_g$ that drives its subsequent energy relaxation through $R_{\text{dyn}}$. These slow decays lead to the Lorentzian voltage noise density between terminals given by (6) for the noise of $v_n(t)$.

Note that currents $I_2 = I_S$ in Figs. (2b) and (3b), independent of the bias $v$, do not contribute to $R_{\text{dyn}}(v)$ but only to the noise in the cavity by driving it with their broadband shot noise of flat spectral density $S_I(f) = 2qI_S A^2/Hz$. In addition, note that, due to the electrostatic coupling between cathode $K$ and the FG in Figs. 1–3 by plate $G$ and to the thermal activity in the system that was kept at some $T > 0$, a Lorentzian voltage noise signal $v_n(t)$ drives an unexpected grid in vacuum diodes, i.e., the electron cloud or FG that faces their cathode. This $v_n(t)$ signal will modulate, with a Lorentzian spectrum, any thermoionic current that escapes from the FG, because electrons that form the plate current of vacuum tubes work under a space-charge-limited $I_P$. Replacing the solid plate $G$ in Fig. 1(a) by a porous plate or FG that allows a small part of the electron flux between plates to escape out of the capacitor, a noise cavity like that of a “black body” is obtained, whose output signal will be an electrical current of mean value $I_p \ll I_{\text{MAX}}$ (e.g., $I_p = 0.01I_{\text{MAX}}$) with an unexpected modulation or fluctuation (noise). Therefore, this escaping current that was collected by a plate (EP) put to the right of plate $G$ in Fig. 1(a) will show a noise with the same Lorentzian spectrum of $v_n(t)$, hence the name LNC, which we will use for a cathode and its FG in front.

At this stage and before we deal with this LNC out of TE, recall that the voltage noise density of (6) comes from a broadband shot current noise in the LNC, which is converted to a voltage noise by the filtering action of the $R_{\text{dyn}}-C_g$ relaxing cell or LNC. In addition, note that, as we have written below (1), the noise power that was dissipated within $C_g$ in TE by its shunting resistance $R$ or the noise power stored in the LNC is $N = kT/\tau$. This power stored in an LNC whose noise bandwidth [10] is $BW_N = \pi f_0/2$ allows us to write it as $N = 4kT \times BW_N$. This result and the $kT$ W/Hz of available thermal noise power that a “conductor of pure resistance $R$” [7] produces in TE due to its thermal contact, by keeping it at temperature $T$, allows us to consider that an LNC that was driven by a shot noise $S_I(f) = 4qI_S (A^2/Hz)$ stores a noise power $N_{\text{TE}} = 4kT \times BW_N W$. This driving of $4qI_S$ (A/Hz) in TE was done by the two uncorrelated shot noises of two opposed currents of mean value $I_S$ each, which means that driving by $S_I(f) = 2qI_S$ due to only one $I_S$ “feeds” the LNC with a noise power, i.e., $N = 2kT \times BW_N$.

Based on this result, which also clarifies why the same mean-square voltage noise was used in [1] for each slice of solid-state relaxing cell, let us obtain the noise spectrum of the LNC out of the TE that was biased by a quiescent voltage $v$. To achieve this goal, we have to first consider the way the noise bandwidth $BW_N$ of this LNC evolves with the bias $v$ to obtain the noise power stored by the LNC and, from this component, the noise spectrum of $v_n(t)$. We also have to consider how the biased cell is driven by shot noise, and for this purpose, we will focus on negative $v$ voltages that surpass a few thermal units $V_T$ to have a constant reverse current in the LNC (e.g., $I_{R-G} \approx -I_S$ in (4) for $u < -3$). Then, we will consider the new time constant $\tau(v)$ due to the reverse bias of the LNC and that the broadband noise density $S_I(f) = 2qI_S A^2/Hz$ is flat up to the new cutoff frequency $f_0(v) = 1/[2\pi R_{\text{dyn}}(v)C_g]$ of the Lorentzian voltage noise density $S_v(f)$ that exists in the LNC biased by the aforementioned negative $v$ values. This last requirement is easily met, because for these reverse bias, the LNC will have an $R_{\text{dyn}}(v)$ that is much higher than $R_{\text{dynTE}}$. In addition, assuming that its capacitance $C_g$ barely changes compared with the exponential increase in $R_{\text{dyn}}(v)$ with reverse $v$, the new $f_0(v)$ will be lower than $f_0$. Therefore, (6) must be halved to consider the LNC that was driven by the shot noise of only one $I_S$ at these reverse bias, and then, we have to consider the proper $f_0(v) = 1/[2\pi R_{\text{dyn}}(v)C_g]$ that was set by the way the LNC relaxes energy by an exponential current decay of time-constant $\tau(v)$ and amplitude $\Delta v = q/\tau(v)$, which takes place after each electron transit. Based on this result and (5), the LNC under a quiescent reverse bias $v$ such that $u \geq 3$ has the following Lorentzian noise spectrum:

$$S_v(f, u) = \frac{kT}{\pi C_g} \times \frac{(1/\tau f) \times \exp(-u)}{1 +(f/f_0) \times \exp(-u)^2}$$

(7)

where it can be checked that integrating this $S_v(f, u)$ from $f = 0$ to $f \to \infty$, the mean-square voltage that was obtained is $(\langle v_n^2 \rangle) = (kT/C_g)/2$ regardless of the value of $u$, which corresponds to a noise power $N = kT/2\pi$ and, thus, half the noise power that existed in the LNC in the TE driven by twice the shot noise power. Note that this $S_v(f, u)$ spectrum of (7) is not the product of $S_I(f) = 2qI_S$ and $|Z(j\omega)|^2$ of the biased LNC, thus indicating that thermal noise is very random such that it lacks the coherency required to make such a product valid and must solely be handled in power. We mean that the random voltage decays that relax energy do not coherently “pile up” to build the rather high voltages in $v_n(t)$ that the $2qI_S \times |Z(j\omega)|^2$ product would give for $R_{\text{dyn}}(v) \to \infty$.

III. Flicker-Noise Synthesizer for EHCs

Equation (7) for the voltage noise density of an LNC under bias $v$ gives a set of Lorentzian spectra, all with the same (amplitude × cutoff frequency) product due to their noise power being $N = 2kT \times BW_N$. These spectra, whose $f_0(v)$ is an exponential function of $v$ for $C_g$, are roughly independent of $v$, as shown in the Bode plots in Fig. 4(a) by dashed lines for a set of LNCS whose bias voltages are linearly spaced, i.e., $u_0 = u_0$, $u_0 = \Delta u$, $u_0 = 2\Delta u$, and so on. This linear series of bias voltages logarithmically spaces the noise amplitudes and their cutoff frequencies in such a way that they build the “constant-step
ladder” in Fig. 4(a), whose slope is 1/f or 10 dB/dec, thus suggesting that the sum of the steps will give a frequency band of 1/f noise for frequencies where the steps exist [1]. This 1/f region will end by a flat region at low frequencies and by a 1/f² roll-off region at high frequencies, as shown in Fig. 4(b), for the sum of ten spectra given by (7) that were logarithmically spaced from 3 to 3000 Hz. This 1/f region that covers three decades only needs seven thermal voltage units in the reverse bias of the aforementioned LNCs (ΔV = u₀ - u₀ = Ln(10²) ≈ 7).

Note that this way of building a 1/f spectrum from a sum of Lorentzians that were properly weighted and detuned has been known as shown in [11], which also cites attempts that were previously done from Lorentzian noise spectra assigned to carrier traps without finding a convincing origin for the 1/f electrical noise.

Nevertheless, the tunability of the LNC that exists around a thermoionic cathode offers new possibilities. Let us consider the cathode of a vacuum diode as a tungsten filament that was electrically heated up to T = 2400 K by the Joule effect of I_F, i.e., an electrical current that was created in the filament by a voltage V_F that linearly drops along it. Therefore, this EHC is not an EC that emits electrons toward the electron cloud that it has in front under a space-charge-limited I_P; however, the theory in [2] for planar ECs under space-charge-limited I_P conditions (e.g., their Child–Langmuir law for I_P) has been proven valid for several times using EHCs; thus, we will assume that an electron cloud or our simplifying FG exists in front of a planar and nonequipotential EHC. If this is the case, this cloud of mobile electrons will be in an equipotential region of some potential V_G; (see Fig. 5) regardless of the region of the EHC that it has in front; otherwise, the cloud would move away. Due to V_F that drops along the EHC, its LNC will have a continuous bias voltage v(y). For an EHC that was heated up to T = 2400 K by a dc voltage V_F = 6 V in Fig. 5, the linear voltage drop along the EHC (y-axis) from V_F(0) = 0 V at point B to V_F(L) = 6 V ≈ 29V_P at point A leads to a tuning voltage v(y) = V_G - V_F(y) in this LNC that continuously varies over 29 thermal units. According to this range of v(y) values in the LNC, the same reasoning that relates three decades of 1/f noise in Fig. 4(b) with a reverse bias span of 2V_P allows us to foresee a span of more than 12 decades for the cutoff frequencies f₀(y) of this LNC.

Before studying this situation in detail, let us first consider this tungsten cathode as a planar EC that was heated under V_F = 0 by a laser power, for example, thus being the planar EC at zero volts in [2] to have a space-limited plate current I_P collected by an EP biased by V_2 V with respect to this EC (see [2, Table III]). For the diode that works under a space-charge-limited I_P in the milliampere range as those used by Johnson [3] (e.g., I_p = 1.6 mA) the corresponding I_MAX will be higher than I_P, I_MAX = 160 mA, for example, following the value in [2, Table III] for a 1-cm² EC of tungsten at 2400 K. For this I_P/I_MAX = 0.01 ratio, [2, Table III] places the PMP at xₘ = d_g = 0.0224 cm from the EC—a d_g value that, for this 1-cm² EC, gives C_g = 3.9 pF for its LNC in TE. From V_F = 207.2 mV at T = 2400 K and I_MAX = 160 mA, we have RdynTE = V_F/I_MAX = 1.29 Ω in parallel with C_g whose τTE = RdynTEC_g of 5 ps gives a cutoff frequency f₀ = 1/(2πτ) = 3.1 × 10¹⁰ Hz. For transit times of electrons in the LNC such that τ ≪ τTE, the plate current I_P of this diode would have a Lorentzian noise with a cutoff frequency of 31 GHz; however, τ are greater than τ in this case; thus, the noise of the currents within the LNC would not noticeably be filtered by C_g and RdynTE.

With regard to the currents in the LNC of this EC, Fig. 6 shows how a mean current I_MAX is emitted toward its FG, which, in turn, reflects toward the EC a roughly equal mean current (∼ I_MAX) to have only a small current I_P that escapes toward the plate of the diode. The built-in voltage V_m of the PMP that would appear between this tungsten EC at T = 2400 K and its FG for this I_P/I_MAX = 0.01 ratio is V_m = -0.95 V, and this PMP appears at xₘ = 0.0224 cm from the EC (see [2, Table III]). Note that, to keep this steady-state situation by a metallic grid or FG placed at d_g = xₘ = 0.0224 cm from the EC, the electric field between the cathode and the FG would be only 42.4 V/cm. This condition would require a negative charge density σFG = 3.7 × 10⁻¹² C/cm² in
the FG (thus, \(2.3 \times 10^7\) electrons per cm\(^2\)). With regard to the external current that the FG needs to supply, i.e., its \(I_{\text{MAX}}\) current toward the EC, note that it comes from the \(I_{\text{MAX}}\) that was emitted from the EC itself. This case mimics the situation where electrons that thermoionically leave the EC are attracted by the EC, thus forming a cloud whose electrostatic coupling with the EC is difficult to handle without the FG approach that we are using.

With this approach, a forward bias in the LNC \((v > 0)\) is a reduction in the \(\sigma_{\text{FG}}\) of the FG to allow a higher \(I_p\) that escapes toward the collecting plate in Fig. 6. In addition, the meaning of a reverse bias in the LNC \((v > 0)\) will be an increase in the \(\sigma_{\text{FG}}\) of the FG to exponentially reduce the escaping \(I_p\) in Fig. 6. A reverse bias higher than 3\(V_T\), which we used to have a constant shot noise power that drives the LNC to obtain (7), simply means that the electron cloud in front the cathode becomes more dense in such a way that practically all the \(I_{\text{MAX}}\) emitted by the cathode is reflected back by the FG toward the cathode or is electrostatically attracted by the EC itself. This reverse bias in the LNC can be predicted in Fig. 5 for the region of the cathode close to point A, which, due to its positive \(V_F\), will attract electrons of the FG more than the region of the cathode close to point B, whose potential is null. Thus, although the thermoionic emission of the EHC in Fig. 5 is constant over its surface (e.g., 160 mA/cm\(^2\) for the tungsten at 2400 K [2]), the plate current \(I_p\) of the diode mostly flows from the region close to point B, and hence, the emission from an EHC is not the 1-D problem that was elegantly solved in [2] for ECs, with this instance being the reason that flicker noise in vacuum tubes has eluded scientists.

After this short study of the equipotential tungsten cathode that was heated by the power laser, let us consider what happens when we apply a voltage \(V_F = 6\) V to heat this EHC up to the same \(T = 2400\) K, because the 12 decades of cutoff frequencies in the LNC due to this \(V_F = 6\) V = 29\(V_T\) give some hope to observe Lorentzian noise in the audio region. To show this result, we will consider the equipotential FG in Fig. 5, which acquires a floating voltage \(V_{\text{float}}\) with respect to point B of this EHC to achieve a dynamical equilibrium with the EHC, making the net transfer of electrons between the EHC and the FG practically null. Only the small current \(I_p\) makes the aforementioned net transfer nonnull, but for \(I_p\) that is much lower than the two opposed \(I_{\text{MAX}}\) of the LNC in TE, we can take the aforementioned net transfer as null and then use [1, eq. (10)] to obtain \(V_{\text{float}}\) that is expressed in thermal units \(U_{\text{float}}\). Note that the exponential \(i = v\) curve for the current between the channel and the floating gate in [1] is equal to (4) for the current between the EHC and the FG, thus making [1, eq. (10)] valid for our case. We have

\[
U_{\text{float}} = \ln \left(\frac{U_d}{1 - \exp(-U_d)}\right) \approx \ln (U_d), \quad \text{for } U_d \geq 3
\]

which, for \(U_d = 6\) V = 29\(V_T\), gives \(U_{\text{float}} = 3.37\). This result means that, at point B in Fig. 5, the LNC has a forward bias \(V_{\text{float}} = 3.37V_T = 698\) mV that will reduce the built-in voltage \(V_n = -0.95\) V or PMP that appeared at \(x_m = 0.0224\) cm from this tungsten cathode that was heated by the power laser to have this \(I_p/I_{\text{MAX}}\) ratio (see [2, Table III]). This forward bias of the LNC at point B \((y = 0)\) linearly decreases as we go toward point A \((y = L)\) in such a way that, advancing 3.37 units along the EHC divided in 29 units \((V_F = 29V_T)\), the bias of the LNC becomes null at point \(y = y_{\text{TE}}\). Going from \(y_{\text{TE}}\) toward point A \((y = L)\), the negative bias of the LNC continuously grows up to \(v = (29V_T - 3.37V_T) = -25.63V_T\). Thus, at point \(y = y_{\text{TE}}\), the LNC relaxes energy with the rate \((\tau_{\text{TE}} = 5\) ps\) that it relaxed when the cathode was heated by the power laser, but at point A, its reverse bias \(v = -25.63V_T\) increases its relaxation time constant up to \(\tau(y = L) = 0.68\) s due to the exponential decrease in \(f_0(v)\) for reverse bias. As a result, the region of the LNC close to point A in Fig. 5 will produce a set of Lorentzian noise spectra with cutoff frequencies that start at \(f_0_{\text{low}} = 1/(2\pi \times 0.68) = 0.23\) Hz. As it will numerically be shown, this continuous set of Lorentzian spectra is viewed as a \(1/f\) noise from 0.23 Hz up to frequencies that are much higher than the megahertz, and this result explains the flicker noise in [3, Part B] for vacuum diodes under space-charge-limited \(I_p\), as we advanced in [12] or at the end of [1, Sec. 6].

Note that the voltage noise generated in the highly reverse-biased region of the LNC (near point A in Fig. 5) is present between the whole cathode and FG electrodes of the LNC, because the distributed circuit or transmission line whose lumped elements are \(C_y\) and a cathode resistance \(R_K = V_F/I_p\) (e.g., 60 \(\Omega\) for \(I_p = 100\) mA typically) is fast enough to allow it at these low frequencies, and the FG reacts quickly enough to be considered equipotential at these frequencies. As a result, the plate current \(I_p\), although escaping mostly near point B, becomes perfectly and linearly modulated by these slow voltage fluctuations that were generated near point A, which are responsible for the low-frequency part of the \(1/f\) noise observed in \(I_p\). To properly consider the different noise spectra that exist at each \(y\) position of the LNC, we have divided its whole length \(L\) along the EHC into small discrete strips of length \(\Delta L = \Delta y\), as shown in Fig. 7, because the LNC has a position-dependent bias \(v(y)\) and thus relaxes energy with a different time-constant \(\tau(y)\) as stated by (7). Therefore, we consider the vacuum diode as formed by \(N\) discrete diodes, with each having a cathode area \(W \times (L/N)\), as shown in Fig. 7. The
two strips labeled as \( C_2 \) and \( C_9 \) on this EHC vertically biased by \( V_F \) would be plates \( K_2 \) and \( K_9 \) of LNCs 2 and 9 of this set of discrete diodes. The FG is equipotential, and each discrete LNC has its own cathode voltage; thus, each cathode FG capacitor \( C_i \) will have its own Lorentzian noise that will be set by a band diagram that lies between the two ones shown in Fig. 8 for points A and B of the LNC.

Due to \( V_F \), the energy barrier for electrons that leave the EHC at points A and B differs by \( qV_F \) [see Fig. 8(a) and (b)], which both have the same barrier maximum or PMP [2] that we considered due to an FG of negative charge at the same distance \( d_y \) from the EHC (\( C_y \approx \) constant). Fig. 8(a) shows the band diagram along the \( B \rightarrow B^* \) arrow in Fig. 5, where the voltage drop along the EHC is still null, thus leaving \( \Phi_1 \) as the barrier for electrons emitted from the EHC to the FG at point B, where the LNC becomes forward biased. Fig. 8(b) is the band diagram along the \( A \rightarrow A^* \) arrow in Fig. 5, where the voltage drop along the cathode is \( V_F \). This instance gives \( \Phi_2 = (\Phi_1 + qV_F) \) as the barrier for electrons that were emitted from the EHC to the FG at point A, where the LNC has its highest reverse bias. The small bode plot labeled as “cavity tuned HIGH” in Fig. 8(a) represents the spectrum of the noise in the first discrete LNC formed by the FG and the first strip of the EHC. One similar bode plot with much lower cutoff frequency and, thus, much higher amplitude (“cavity tuned LOW”) is shown in Fig. 8(b) for the last discrete LNC formed by the FG and the last strip of the cathode. The electron fluxes that escape from this set of LNCs at different \( y \) positions share the same linear modulation by the small noise voltages that give rise to \( v_n(t) \); thus, the current \( I_P \) will show a modulation proportional to this sum of Lorentzian noise voltages that, when converted into a voltage noise by \( R_P \), will be observed as a flicker voltage noise added to the dc plate voltage \( V_P \) in Fig. 5. This case explains flicker noise in vacuum tubes as due to the thermal noise of a capacitor disturbed by a bias applied to the device and, thus, by the same basic theory that explained \( 1/f \) resistance noise in solid-state devices [1].

Before handling this continuous set of Lorentzian noise terms, let us consider the thick Lorentzian spectrum that emerges over the \( 1/f \) line in Fig. 4(a). This factor is the noise that would appear in the circuit in Figs. 5 and 7 if the cathode was heated under \( V_F = 0 \) V by the aforementioned power laser. In this case, each discrete LNC in the vacuum diode would have the same Lorentzian spectrum of noise and would relax a power of \( \Delta y/L \) times the power of this thick Lorentzian noise whose \( f_0 \) is equal to that existing at \( y = y_{TE} \) for the EHC under \( V_F = 6 \) V. Therefore, the contribution of each discrete LNC of area \( W \times \Delta L \) in Fig. 7 to the total noise of \( I_P \) will be a fraction \( \Delta L/L \) of the noise power density that (7) gives for the whole LNC in front of a planar EC and under bias \( v \). Thus, each differential part of vacuum diode of width \( W \) and length \( \Delta L \rightarrow \Delta L \) in Fig. 7 whose differential LNC is reverse biased by more than \( 3V_T \) will add a differential term of noise power density to \( v_n(t) \) given by

\[
\partial S_V(f, u) = \frac{kT}{\pi C_g} \frac{1}{f} \int \frac{(f/f_0) \times \exp(-u)}{1 + ((f/f_0) \times \exp(-u))^2} \frac{\partial L}{L}. \tag{9}
\]

Integrating along the \( y \)-axis (see Fig. 7), we find \( \partial L = \partial y \), and due to the linear drop of \( V_F \) along \( L \), we find \( \partial L/L = \partial v/V_F \) and \( \partial L = \partial u/U_{F} \) for \( V_F/V_F = U_F \). Using these results to integrate from \( u = -(U_F + U_{float}) \) as the bias of the LNC at point A to \( u = -3 \) to collect only the contributions of those differential LNCs with enough reverse bias to make (7) valid, the continuous distribution of voltage noise spectra in \( v_n(t) \) is

\[
S_V(f, U_F) = \frac{kT}{\pi C_g U_F} \frac{1}{f} \int \frac{(f/f_0) \times \exp(-u)}{1 + ((f/f_0) \times \exp(-u))^2} \times \partial u. \tag{10}
\]

Using \( \Theta = (f/f_0) \times \exp(-u) \), we have \( \partial \Theta = -\Theta \partial u \), and the aforementioned integral becomes

\[
S_V(f, U_F) = \frac{kT}{\pi C_g U_F} \frac{1}{f} \int \frac{\partial \Theta}{\Theta^2} \tag{11}
\]

where the new limits are \( \Theta_A = (f/f_0) \times \exp(3) \) and \( \Theta_B = (f/f_0) \times \exp(U_A - U_{float}) \). For frequencies \( f \) that make \( \Theta_2 \gg 1 \) and \( \Theta_1 \ll 1 \) (which means that \( f_{float} = 0.23 \) Hz \( \ll f \ll 1.5 \) GHz in our example, with \( V_F = 29V_T \), the \( \tg^{-1} \) function from the integral in (11) gives a term that is very close to \( \pi/2 \) that converts (11) into this the following equation:

\[
S_V(f, U_F) \approx \frac{1}{2} \frac{kT}{\pi C_g} \frac{1}{U_F}. \tag{12}
\]
which states that, between a planar EHC in vacuum and its electron cloud in front, there is a voltage noise with the following features.

1) It is due to the thermal noise (fluctuation) of the electrostatic energy of a parasitic capacitance \(C_p\) due to the electrostatic coupling between the cathode and its surrounding electron cloud.
2) It has a \(1/f\) spectrum region if the voltage \(V_F\) that was applied to heat the cathode surpass several thermal units of voltage at the cathode temperature \(T_F\).
3) Its \(1/f\) power law can cover several decades of frequency, but it will end by a flat region at low-enough frequencies.
4) Its departure from the \(1/f\) power law at high frequencies can be hidden by other noises as thermal noise in \(R_P\).

IV. Flicker Noise From Filament Cathodes That Face Collecting Plates

The aforementioned flicker noise generated by an EHC is due to a distributed bias within the device that modulates an energy barrier for electrons that leave the cathode. This idea of an energy barrier being modulated by the bias applied during the measurement [1] or to make the device work (e.g., \(V_F\) for heating an EHC) can also explain the flicker noise of vacuum diodes under saturated \(I_P\) as described in [3, Part A]. These devices, without the electron cloud or FG that limits their \(I_P\), would seem to be out of our theory, but this instance is only apparent. One striking comment in [3] about the circuit for measuring noise in diodes with saturated \(I_P\) was that the output resistance of the diode would be in parallel with the input resistance of the amplifier that was used to amplify the noise in the tuned circuit in [3]. Although it is familiar for electrical circuits, this case sounds strange for a diode under saturated \(I_P\) whose dynamical resistance would vanishingly be high if one neglects the Schottky effect, which makes the thermoionic emission depend on the voltage applied to the plate [4]. In other words, small changes in the plate voltage of a diode under saturated \(I_P\) would have to be quite inefficient to modify its \(I_P\), which is only limited by the emission rate of the cathode. However, the aforementioned comment led us to consider how the plate-cathode voltage of these diodes could affect the noise present at their output.

With regard to the diodes in [3], these parts were vacuum triodes whose grid and plate terminals were tied together and were described as follows: “...Standard Western Electric 102-D audions with plane-parallel plates and grids and a V-shaped ribbon of oxide-coated platinum as the cathode. These will be referred to as tubes No. 2 and No. 3. Tube No. 1 was similar in structure but had a filament of pure tungsten.” The results in [3] indicated that the value of the charge \(q\) that enters in the expression of \(S_L(f) = 2qI_S A^2/Hz\) at low frequencies seemed to increase as frequency decreased, as if the cathode emission was less uniform than electron by electron (e.g., carried out by charge packets greater than \(q\)). This case was the first attempt to explain the flicker noise of spectrum proportional to \(1/f^\beta\), where \(\beta \approx 1\). Nevertheless, our theory can give an electrical reason to find flicker noise in the saturated \(I_P\) of vacuum diodes that does not conflict with electrons that are individually emitted. To do so, we will again consider a parasitic floating electrode and the disturbing action of a dc bias in the device, which are both overseen over the course of time.

Fig. 9 is the cross section of a thin filament that runs parallel at a distance \(d_P\) from a metallic plate that was placed to collect the electrons that it thermoionically emits. Taking the length \(L\) of the filament as \(L \gg d_P\), we can use a 1-D approach of the method of images [13] to obtain the electrostatic potential created by this system of conductors. Fig. 9 corresponds to a fixed position \(y\) in Fig. 5, which can be \(y = 0\) (point B) for simplicity. We will start by considering that the dc voltage \(V_P\) between the filament and the plate is null and that the hot filament thermoionically emits electrons. According to [2] and our FG approach, a cylindrical FG with radius \(d_g\), will exist around the filament (shown as a dotted line in Fig. 9). This FG leads to an energy barrier of height \(qV_{m\text{in}}\) eV along the circumference of radius \(d_g\) for electrons that leave the cathode, and for \(V_P = 0\) V, a small but not null plate current \(I_{P\text{th}}\) will flow due to the nonnull kinetic energy of the emitted electrons (see the exponential region of a vacuum diode in [4]). As \(V_P\) is raised, the FG that faces the plate at position \((\alpha = 0, r_a = d_g)\) is weakened, thus reducing the energy barrier viewed along the \(\alpha = 0\) direction to \(qV_{\text{net}}(\alpha = 0) = (qV_{m\text{in}} - qV_{\text{appl}})\), where \(V_{\text{appl}}\) is the potential created by this system of conductors at position \((\alpha = 0, r_a = d_g)\) by \(V_P\) applied between plate and cathode. Using the results based on [13] in Fig. 9, we have

\[
V_{\text{appl}}(r_a, r_b) = \frac{\rho_L}{2\pi \varepsilon} \times \ln \left( \frac{r_a}{r_b} \right) \tag{13}
\]

where \(\rho_L\) is the positive linear charge density in the image filament due to \(V_P\) that makes the plate positive with respect to cathode. Equation (13) shows that a cylinder of radius \(r_a = d_g\), where the FG would be for \(V_P = 0\), is not an equipotential surface, and thus, the reduction of the energy barrier of the FG around the cathode will vary as we move from \(\alpha = 0\) to \(\alpha = 2\pi\) along the circumference of radius \(r_a = d_g\). To use angle \(\alpha\), we have

\[
V_{\text{appl}}(r_a, \alpha) = \frac{\rho_L}{4\pi \varepsilon} \times \ln \left( \frac{(r_a)^2}{(2d_P)^2 - 4d_P r_a \cos \alpha + (r_a)^2} \right) \tag{14}
\]

It is an expression that, together with the data from [2], will allow us to sketch how the barrier for thermoionic emission varies around the cathode filament. According to [2, Table III, first row], for a planar EC of tungsten at \(T = 2400\) K that faces...
an EP at \( d_p = 0.5 \) cm, we find that the PMP is at \( x_m = d_g = 0.074 \) cm from the EC when the \( I_p / I_{MAX} \) ratio is 0.001 for a plate voltage \( V_p = 2.5 \) V (\( V_p = V_2 \) in the aforementioned table). For these conditions, the potential of the PMP is \( V_m = -1.43 \) V, which, with our FG approach, means that an energy barrier of 1.43 eV exists at \( r_a = 0.074 \) cm in Fig. 9 for electrons that leave the tungsten filament at \( T = 2400 \) K. Although the PMP or FG position varies as the energy barrier is reduced by \( V_p \), we will consider a roughly constant \( r_a \approx 0.074 \) cm for clarity. Considering that the equipotential surfaces in Fig. 9 are cylinders whose centers are somewhat displaced toward the left of the filament, the problem of a metallic filament of a nonnull radius \( r_F \) whose surface is equipotential is equivalent to that of a charge line of null radius slightly placed to the right of the center of the actual filament of radius \( r_F \) (see [13] for details). Nevertheless, for the simple treatment that we will do here, (13) and (14) are enough to show the barrier modulation around a cathode filament of radius \( r_F = 0.1 \) mm \( \ll r_a = 0.074 \) cm, which we will use to estimate the barrier modulation due to \( V_p \).

The crowding of electric field lines next to this filament makes the situation in Fig. 9 quite different from the system in [2], where the EC was not a thin wire but another plate parallel to the collecting one. Thus, the voltage \( V_2 = 645 \) V in [2] to remove the energy barrier in front of the cathode, which was applied between plate and cathode separated by \( d_p = 0.5 \) cm, gives an electric field \( E = 1.29 \) kV/cm that leads to a 1.43-V voltage drop at \( 0.011 \) mm from the cathode. To have a similar field strength in Fig. 9 when going from the cathode wire of radius \( r_F \) toward the plate with \( \alpha = 0 \), we have to consider \( r_b = (2d_p - r_a) \) in (13) to differentiate it with respect to \( r_a \) to obtain the electric field next to the metal wire under \( \alpha = 0 \).

By doing so, we have

\[
E_{\text{Appl}}(r_a, \alpha = 0) = \frac{\rho_L}{2\pi\varepsilon} \left( \frac{1}{r_a} + \frac{1}{(2d_p - r_a)} \right) \quad (15)
\]

To have \( E_{\text{Appl}}(r_a, \alpha = 0) = 1.29 \) kV/cm at \( r_a = r_F \) and considering \( r_F \neq 0 \), a value \( \rho_L/(2\pi\varepsilon) = 12.9 \) V results, which, according to (14), allows us to sketch how the energy barrier around the cathode at \( r_a = d_g \) is modulated by this \( V_p = V_{\text{notch}} \) that, by making such a barrier for \( \alpha = 0 \) null, would open a notch in the cylindrical barrier around the cathode for electrons that were emitted with \( \alpha = 0 \), thus allowing them to escape from the LNC without being reflected back toward the cathode by the FG. This way, a saturated \( I_p \) through such a notch would flow for \( V_{\text{notch}} \approx -59.28 \) V, as obtained by (14) with \( r_a = r_F \), which is much lower than the aforementioned \( V_2 = 645 \) V due to the crowding of electric field lines that take place in the filament that is absent for the planar EC in [2].

With regard to the barrier height modulation around the cathode, (14), with \( \rho_L/(2\pi\varepsilon) = 12.9 \) V applied to the circum-

<table>
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<th>Angle ( \alpha )</th>
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<th>( \pi/6 )</th>
<th>( \pi/3 )</th>
<th>( \pi/2 )</th>
<th>( 2\pi/3 )</th>
<th>( 5\pi/6 )</th>
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<tr>
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<td>-32.74</td>
<td>-33.13</td>
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<td>8.69</td>
<td>9.21</td>
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V. CONCLUSION

The flicker noise of vacuum tubes has also obeyed the new theory that considers the thermal fluctuations of electrostatic energy stored in the devices, usually by parasitic relaxing cells whose relaxing time constants are disturbed by a dc bias applied to the device. These findings have shown that the modulation of an energy barrier in a device by its own biasing, for example, is a source of \( 1/f \) noise. Given the energy barriers
(e.g., electrical, magnetic, and chemical) that can be disturbed this way, this novel theory based on measurement has agreed with the ubiquitous character of the $1/f$ electrical noise found in electronic devices and, perhaps, in systems that store energy other than electrostatic ones.

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