COMPUTER SIMULATION OF ELECTRONIC DEVICE FOR GENERATION OF ELECTRIC OSCILLATIONS BY NEGATIVE DIFFERENTIAL CONDUCTIVITY OF SUPERCOOLED NANOSTRUCTURED SUPERCONDUCTORS IN ELECTRIC FIELD

Todor MISHONOV, Victor DANCHEV, Albert VARONOV

Sofia University St. Kliment Ohridski, Sofia, Bulgaria, EU,
mishonov@bgphysics.eu, spectrefdx@gmail.com, akofmg@gmail.com

Abstract

We use the formerly derived explicit analytical expressions for the conductivity of nanostructured superconductors supercooled below the critical temperature in electric field. Computer simulations reveal that the negative differential conductivity region of the current-voltage characteristic leads to excitation of electric oscillations. We simulate a circuit with distributed elements as a first step to obtain megahertz oscillations. This gives a hint that a hybrid device of nanostructured superconductors will work in terahertz frequencies. If the projected setup is successful, we consider the possibility to be put in a nanosatellite (such as a CubeSat). A study of high temperature superconductor layers in space vacuum and radiation would be an important technological task.

Keywords: Thin nanostructured superconductor film, negative differential conductivity, oscillations

1. INTRODUCTION

The purpose of the present work is to present a numerical simulation, which shows the generation of high-frequency oscillations created by a thin superconducting film supercooled bellow the critical temperature T_c in external electric field E. The idea was first proposed more than 10 years ago [1] and now we are giving details on how to start the experimental work using radio frequency oscillations with distributed elements (resistors, capacitors and inductors). The main idea is to insert a supercooled superconductor with negative differential conductivity as an active element in a resonance circuit. The simulation presented in this work aims to trigger the analogous development of the terahertz region where the resonance circuit will be implemented on the same hybrid nanodevice which will emit coherent terahertz waves.

2. FLUCTUATION CONDUCTIVITY IN ELECTRIC FIELD

Our starting point is the result for the two-dimensional fluctuation current density j_{2D} in external electric field [2-3] see also [4]

$$j_{2\mathrm{D}} = \sigma_0 \left[S_n + S(\epsilon, \beta) \right] E, \tag{1}$$

where β is the dimensionless electric field and ϵ is the reduced temperature

$$\beta = \frac{\pi e\, \xi E}{16\, k_{\mathrm{B}} T_c} = \frac{e \xi E}{\hbar/\tau_0}, \qquad \epsilon = \ln\frac{T}{T_c} \approx \frac{T - T_c}{T_c} \tag{2}$$

defined by the coherence length ξ

$$-T_c \left.\frac{\mathrm{d}B_{c2}}{\mathrm{d}T}\right|_{T_c} = \frac{\Phi_0}{2\pi \xi^2}, \qquad \Phi_0 = \frac{\pi\hbar}{|e|}, \tag{3}$$

the critical temperature T_c or a time constant τ_0, related to the relaxation of the superconducting order parameter

$$\frac{\hbar}{\tau_0} = \frac{16\, k_{\mathrm{B}} T_c}{\pi}, \tag{4}$$

where k_B is the Boltzmann constant. The constant $\sigma_0 = e^2/16\hbar$ with dimension of conductivity represents the Aslamazov-Larkin conductivity above T_c for evanescent electric field $E \to 0$ $\sigma_{AL} = e^2/16\hbar\epsilon$ for $\epsilon>0$. The normal conductivity σ_n is parameterized by the dimensionless $S_n = \sigma_n/\sigma_0$.

The dimensionless function $S(\epsilon, \beta)$ of reduced temperature ϵ and electric field β

$$S(\epsilon,\beta) = \int_0^\infty \exp\left(-\epsilon v - \frac{\beta}{3} v^3\right) \mathrm{d}v, \tag{5}$$

describing the fluctuation conductivity is depicted in **Figure 1**.

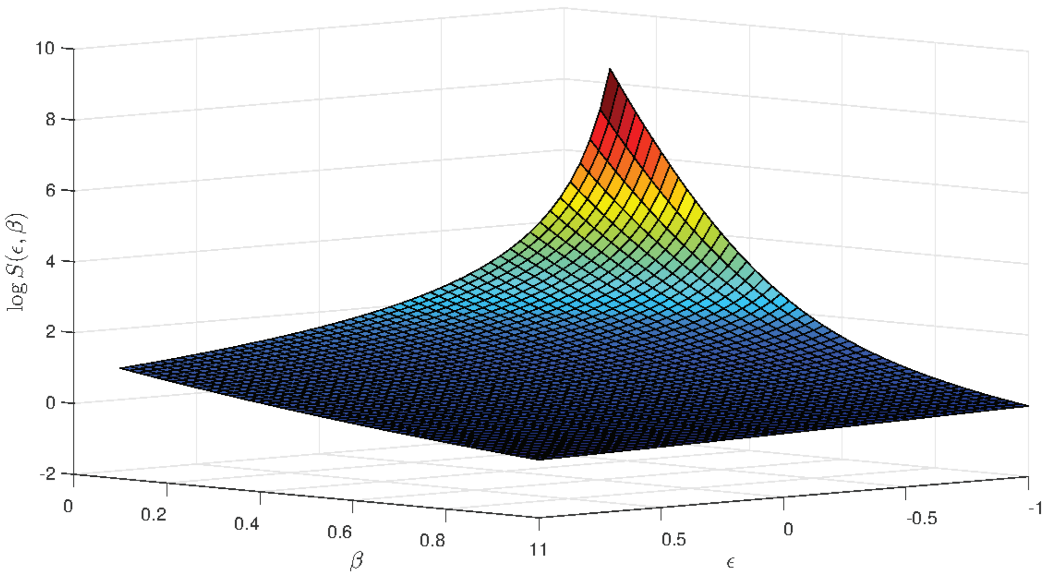

Figure 1 The logarithm of the dimensionless conductivity $S(\epsilon, \beta)$ as a function of reduced temperature ϵ and dimensionless electric field β, equation (5).

This formula for the current equation (5) is a consequence of time-dependent Ginzburg-Landau equation, which is applicable below T_c if the coherent superconducting order parameter is destroyed by a constant electric field. For $\epsilon = 0$ the integral is elementary, while in other cases the substitution $u = |\epsilon| v$ reduces the integral to well-known special functions.

For low frequencies where the heat capacity of the superconductor is negligible, the temperature of the superconducting layer is determined by the Ohmic heating per unit area $E\, j_{2\mathrm{D}}(E)$ and interface boundary resistance R_θ

$$E\, j_{2\mathrm{D}}(E,T) = \frac{T - T_\mathrm{s}}{R_\theta}, \qquad \rho_\theta = \frac{16\, k_\mathrm{B}^2 T_c R_\theta}{\pi^2 \hbar \xi^2}, \tag{6}$$

where ρ_θ is a convenient dimensionless parameter useful for the further analysis and T_s is the substrate temperature. Until the critical temperature T_c can be found by fitting the temperature dependence of the resistivity above T_c, the coherence length ξ can be extracted without applying magnetic field B from the non-linear fluctuation conductivity [5] at T_c

$$j_{2\mathrm{D}} = \frac{3^{1/3}\Gamma\left(\frac{4}{3}\right)}{2^{4/3}\hbar} \left(\frac{k_\mathrm{B} T_c}{\pi e\, \xi}\right)^{2/3} E^{1/3} + \sigma_n E, \qquad T = T_c\,. \tag{7}$$

Since the fluctuational current formally tends to infinity at evanescent electric field bellow T_c, one can easily derive the asymptotics

$$j(E)E]_{\mathrm{E}\to 0} = (T_c - T_\mathrm{s})/R_\theta = \frac{1}{lw} U I(U)]_{U\to 0}\ , \tag{8}$$

which allows us to determine the interface conductance R_θ. Or else the current

$$j(E) = \frac{T_c - T_s}{R_\theta E} + \sigma_n E, \quad (9)$$

meaning that we have hyperbolic approximation for the current-voltage characteristic. Here the voltage *U* and the current *I* are given through the strip length *l* and its width *w*. They are related to $j(E)$ and *E* through $I = j_{2D}\, w$, $U = E\, l$. Below the critical temperature $T<T_c$ at small electric fields the current is significant and the temperature of the superconductor has to be calculated in a self-consistent way solving simultaneously equation (6) and equation (1) shown in **Figure 2**.

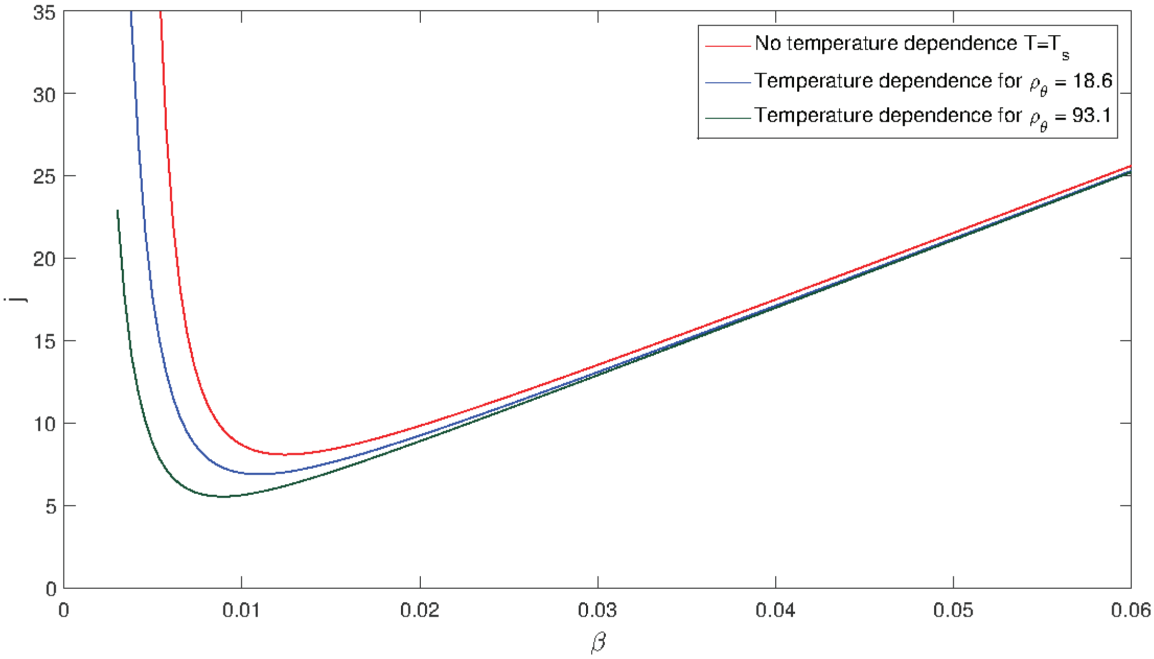

Figure 2 Dimensionless current-voltage characteristics $j_{2D}(E)$ or rescaled *I(U)* based on equation (1) and equation (6) for different interfacial thermal resistances

The shape of the thin film is not necessarily a strip. For example it can be in Corbino geometry, a narrow ring between radii R_1 and R_2 with $l=R_2-R_1<<R_2$ and $w=2\pi R_1$. Specifically for high T_c superconductors, the frequency $1/\tau_0$ is in the terahertz range and for them the above-derived static formulas for the current are valid practically for the whole radio frequency range. In the next section, we present a circuit working within the framework of the theory presented so far.

3. CIRCUIT GENERATING OSCILLATIONS

The circuit for generation of stable oscillations by using negative differential conductivity in supercooled superconductors is shown in **Figure 3**.

One can easily see the parallel *LC* resonance circuit generating the oscillations. In short, the negative differential resistivity R_{SC} amplifies the generated oscillations, while the two oppositely connected diodes D_1 and D_2 limit the amplitude of the oscillations. Applying Kirchoff's laws, the dynamical laws governing the currents and voltages, to the circuit in **Figure 3** the current and voltage equations are easily found to be

$$\mathcal{E} - R_{\mathrm{pot}}\, I_1 - U - \mathcal{L}\dot{I}_1 = 0, \quad (10)$$

$$\dot{U} - \frac{2}{C_0} I_2 - \frac{I_6}{C} = 0, \quad (11)$$

$$\frac{I_6}{C} - r\dot{I}_7 - L\ddot{I}_7 = 0, \quad (12)$$

$$I_5 - F(U) = 0, \quad (13)$$

$$I_1 - I_2 - I_5 = 0, \quad (14)$$

$$I_2 - I_3 - I_6 = 0, \quad (15)$$

$$I_3 - I_4 - I_7 = 0, \quad (16)$$

This system of equations governs the circuit operation.

The current through the diodes D_1 and D_2 (I_4) is governed by the volt-ampere characteristic

$$I_4 = \sigma_d\big[(\mathcal{E}_L - U_0)\theta(\mathcal{E}_L - U_0) + (\mathcal{E}_L + U_0)\big(1 - \theta(\mathcal{E}_L + U_0)\big)\big], \quad (17)$$

where $\mathcal{E}_L$ is the voltage between the two ends of the inductance L, σ_d is the diode's conductance when it is "open" and U_0 is its opening voltage. Obviously I_4 is entirely determined by the inductance voltage, which from equation (17) is completely determined by I_7 and $\dot{I}_7$.

Eliminating I_2, I_3, I_5 and I_6 and defining the additional functions $Y(t) = \dot{I}_7(t)$ and $D(x) = \sigma_d\big[(x - U_0)\theta(x - U_0) + (x + U_0)\big(1 - \theta(x + U_0)\big)\big]$, we can rewrite this system as

$$\dot{I}_1 = \frac{\mathcal{E}}{\mathcal{L}} - \frac{R_{\text{pot}}}{\mathcal{L}} I_1 - \frac{U}{\mathcal{L}}, \quad (18)$$

$$\dot{I}_7 = Y, \quad (19)$$

$$\dot{U} = \left(\frac{2}{C_0} + \frac{1}{C}\right)(I_1 - F(U)) - \frac{1}{C}\,(D(rI_7 + LY) + I_7), \quad (20)$$

$$\dot{Y} = \frac{1}{LC}\,(I_1 - I_7 - F(U) - D(rI_7 + LY)) - \frac{r}{L} Y. \quad (21)$$

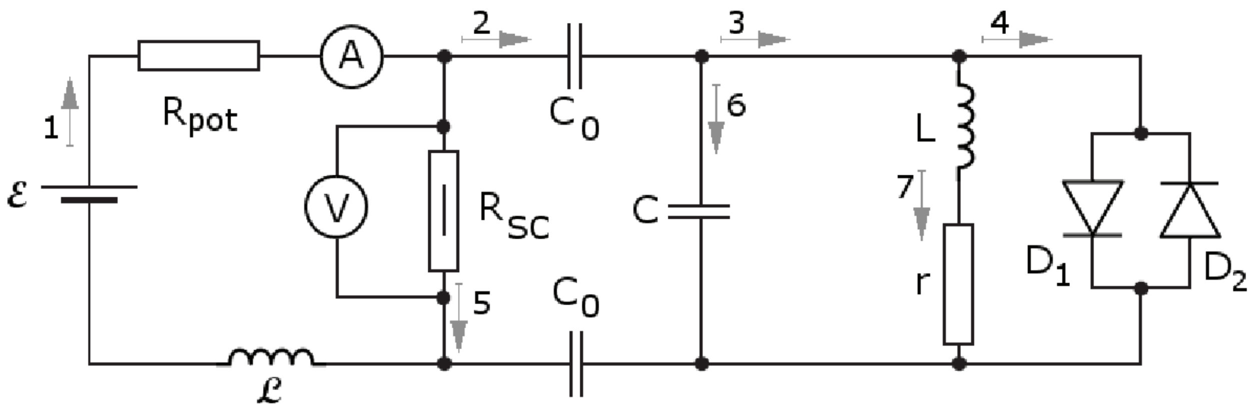

Figure 3 Circuit with negative differential conductivity R_{SC}^{-1} of a superconductor supercooled below T_c in an external electric field. The direct current is created by a battery $\mathcal{E}$ and the current I_1 (denoted by the arrow with number 1 in the figure) measured by the ammeter A is regulated by the potentiometer R_{pot}. High-frequency current through the battery is stopped by the large inductance $\mathcal{L}$ and voltmeter V measures the dc voltage of the thin superconductor film. The dc current supply is galvanically separated from the parallel LC resonator by the large capacitors C_0. The resonance frequency $\omega_0 = 1/\sqrt{LC}$ is fixed by the values of the small capacitor C and the small inductance L with internal resistance r. The amplitude of the electric oscillations is limited by diodes D_1 and D_2. The different currents in the circuit denoted in the figure by their numbers only, participate in the circuit equations (10)-(16).

4. RESULTS

The calculated oscillations generated by the thin supercooled below T_c superconductor from the circuit in **Figure 3** are shown in **Figure 4** with the numerical values in **Table 1**.

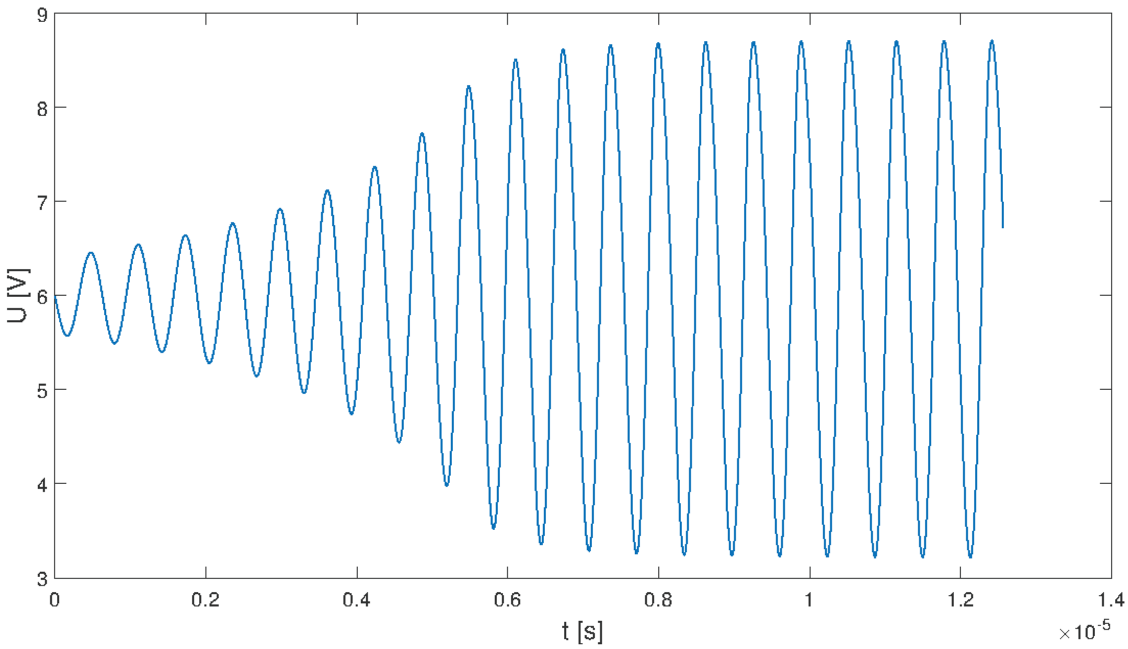

Figure 4 Stable electric oscillations generated by the circuit in **Figure 3** using the values in **Table 1**

Table 1 Numerical values of the circuit elements and parameters from Figure 3 and the equations (10)-(16)

Element	Value	Parameter	Value
$\mathcal{E}$	6 V	l	2 mm
R_{pot}	1 kΩ	w	2 mm
$\pounds$	100 μH	ξ	2 nm
C_0	100 μF	S_n	137
C	10 nF	T_s	80 K
L	1 μH	T_c	90 K
r	0.1 Ω		
U_0	2 V		
σ_d	0.1 Sm		

The oscillations are in the megahertz region as it is expected from the values of L and C from **Table 1**. Both diodes limit the oscillations amplitude preventing exponential grow. These results give an optimistic estimate that it is worth starting an experimental research with the available nanostructured samples.

5. CONLUSIONS

We demonstrate megahertz range of electric oscillations created by the negative differential conductivity in external electric field of supercooled below T_c superconductor. Using distributed elements, the frequency of generations is fixed but using as a resonator 2D plasmons [6] the resonance frequency can easily reach terahertz range. The theory of damping rate of 2D plasmon will be given elsewhere.

The development work should start with investigation of current voltage characteristics of a nanostructured superconductor similar to a field effect transistor. The area of source and drain should be maximal in order to ensure high currents. If the gate is implemented by de-pairing magnetic material, the described sample will be a new type superconducting field effect transistor operating in the terahertz range. Crucial starting point will be observation of annulation of differential conductivity at decaying electric field below T_c. It was suggested by Gor'kov [7] which tried to interpret the generation of high-frequency electric oscillations in thin superconducting films observed half a century ago [8]. Now the time has come to develop technical applications based on hybrid nanostructured superconductors.

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