Effect of transport current on suppression of superconductivity with ultrashort laser pulse

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Abstract. We study the suppression of superconductivity with ultrashort laser pulse in the presence of transport current. The theoretical model is based on the BCS relations for the superconducting state coupled with kinetic equations for nonequilibrium Bogoliubov quasiparticles and phonons. The results of numerical simulation for picosecond and femtosecond laser pulses of optical and infrared ranges are given. We discuss the effects of main problem parameters, including the current density.
1. Introduction

There exists the important task of developing fast switching devices for use in high-current superconducting applications, e.g. current limiters \[1\], NMR/MRI tomography magnets \[2\], magnetic levitation devices \[3\], inductive pulsed power supplies \[4\] and others. There are several control principles used in superconducting switches: thermal \[5\], current-based \[6\], magnetic \[7, 8\], laser \[9\] or combinations \[10\]. As the creation of current or magnetic field pulses shorter than \(\sim 10^{-6}\) seconds is difficult, using the laser for fast switching seems the most preferable. The estimation of the shortest switching time is given by the relaxation time of electron subsystem in superconductors \(\sim 10^{-13}\) seconds and lower, and can be possibly achieved with femtosecond pulses \[11\].

The nonequilibrium state of excess quasiparticles and phonons in the superconductor can be treated differently, depending on the duration of the excitation. In the case of source with slowly changing or constant intensity, the stationary nonequilibrium distribution function is usually considered, depending on the excitation parameters such as power, spectral width etc. \[12, 13, 14\]. One of the prominent results is the superconductivity stimulation by the microwave field \[15\]. On the other hand, to study the strongly nonequilibrium state after nearly-instant excitation e.g. absorption of gamma radiation quantum \[16\], the more general approaches are preferable, such as the time-dependent Green’s functions method \[17\], Keldysh formalism \[18, 19\], and Eliashberg’s theory \[20\].

The excitation of superconductor with ultrashort laser pulse discussed in this work, corresponds to the duration intermediate between these extreme cases. Following the typical experimental results \[21, 22\], there are two distinct stages in the reaction of the superconductor. First, the deviation from the equilibrium develops further after the excitation in the sub-picosecond time scale, which is governed by the electron-electron interaction. After that, the superconducting state returns relatively slowly to the equilibrium with characteristic times of tens of picoseconds, due to the electron-phonon interaction. The relaxation of the excess nonequilibrium quasiparticles and phonons can be described by the phenomenological Rothwarf-Taylor model \[23\, 11\].

In this work, the duration of superconductivity suppression process determining the potentially achievable operating speed, is studied. We use the qualitative theoretical model based on the Bardeen-Cooper-Shrieffer (BCS) theory coupled with kinetic equations for high-energy quasiparticles and phonons, demonstrating the experimentally known characteristic behaviour with fast stage of the excitation development. The results of the numerical simulation for typical problem parameters are presented. The dependence of the superconductivity suppression time on the current density and laser wavelength is discussed.

2. Theoretical model

We consider the limited area of superconductor irradiated by the optical pulse of finite duration generating the nonequilibrium Bogoliubov quasiparticles. The recombination
of two quasiparticles into a Cooper pair creates the phonon carrying the extra energy, while the backwards process converts the phonon and Cooper pair into two quasiparticles. This energy exchange between subsystems allows the thermalization of the excited nonequilibrium particle densities at relatively short times. After that, the excess quasiparticles and phonons decay with corresponding characteristic times resulting in the relaxation of the superconducting state.

To affect the superconducting order parameter, the quasiparticle energy should be lower than Debye energy ($\xi_k < h\omega_D \sim 10^{-2}$ eV). However, the quasiparticles generated by the absorption of the optical quantum of frequency $\omega$ have much larger energy $\approx \frac{\hbar \omega}{2} \sim 1$ eV and thus need some time to reach the effective range with relaxation. We should mention the special case of THz radiation [24], in which the radiation quantum energy is comparable to the energy gap and the generated quasiparticles affect the superconductivity immediately. In this work, we limit the consideration to the laser pulses of optical and near-infrared ranges.

Such formulation allows to avoid the difficulties of applying the theoretical approach based on Green’s functions [16, 25]. Indeed, as the superconducting state is affected by the quasiparticles only near the Fermi surface, the optically-generated excitations have much higher energy and can be described with simple kinetic equations coupled with BCS relations for the order parameter in a self-consistent way. This approach is feasible at time scales long enough for the BCS state to adjust to the varying number of excitations, i.e. $\gtrsim 10^{-14}$ s.

Main relations of the BCS theory:

$$\Delta = V_0 \sum'_{\mathbf{k}} u_\mathbf{k} v_\mathbf{k} (1 - n_{\mathbf{k},\uparrow} - n_{-\mathbf{k},\downarrow}),$$  \hspace{1cm} (1)

$$u_\mathbf{k}^2 = \frac{1}{2} \left( 1 + \frac{\xi_\mathbf{k}}{\varepsilon_\mathbf{k}} \right),$$  \hspace{1cm} (2)

$$v_\mathbf{k}^2 = \frac{1}{2} \left( 1 - \frac{\xi_\mathbf{k}}{\varepsilon_\mathbf{k}} \right),$$  \hspace{1cm} (3)

$$\xi_\mathbf{k} = \frac{\hbar^2 k^2}{2m} - E_F,$$  \hspace{1cm} (4)

$$\varepsilon_\mathbf{k} = \sqrt{\xi_\mathbf{k}^2 + \Delta^2},$$  \hspace{1cm} (5)

where $V_0$ is the interaction parameter, $n_{\mathbf{k},\uparrow}$ and $n_{\mathbf{k},\downarrow}$ are the numbers of electrons with wave number $\mathbf{k}$ and the respective spin projections, the dash at the sum denotes the restriction for the electron energies $|\xi_\mathbf{k}| < h\omega_D$, $\omega_D$ is the Debye frequency, $m$ is the electron mass, $E_F$ is the Fermi energy, and $\Delta$ is the superconducting energy gap (order parameter).

The elementary excitations in a superconductor are the Bogoliubov quasiparticles with energies $\varepsilon_\mathbf{k}$ and secondary quantization operators $\hat{\gamma}^\dagger_{\mathbf{k}\sigma}$, $\hat{\gamma}_{\mathbf{k}\sigma}$ related to the initial electron operators $\hat{a}^\dagger_{\mathbf{k}\sigma}$, $\hat{a}_{\mathbf{k}\sigma}$ as follows:

$$\hat{a}_{\mathbf{k}\uparrow} = u_\mathbf{k} \hat{\gamma}_{\mathbf{k}\uparrow} + v_\mathbf{k} \hat{\gamma}^\dagger_{-\mathbf{k}\downarrow},$$  \hspace{1cm} (6)

$$\hat{a}^\dagger_{-\mathbf{k}\downarrow} = -v_\mathbf{k} \hat{\gamma}_{\mathbf{k}\uparrow} + u_\mathbf{k} \hat{\gamma}^\dagger_{-\mathbf{k}\downarrow}.$$
Writing the Hamiltonian of the system in the quasiparticle basis and adding the electron-electron and electron-phonon interactions:

\[ \hat{H} = \sum_{k\sigma} \varepsilon_k n_{k\sigma} + \sum_q \tilde{\varepsilon}_q \tilde{n}_q + \hat{H}_{e-e} + \hat{H}_{e-ph}, \]

\[ \hat{H}_{e-e} = U_0 \sum_{kmp} \hat{\gamma}_{k\sigma}^\dagger \hat{\gamma}_{m\sigma}^\dagger \hat{\gamma}_{m\sigma} \hat{\gamma}_{p\sigma}, \]

\[ \hat{H}_{e-ph} = M_0 \sum_{kq\sigma} \left( \hat{b}_q^\dagger \hat{a}_{k+q,\sigma} + H.c. \right), \]

where \( \hat{b}_q, \hat{b}_q^\dagger \) denote the phonon creation and annihilation operators, \( n_{k\sigma} = \hat{\gamma}_{k\sigma}^\dagger \hat{\gamma}_{k\sigma} \), \( \tilde{n}_q = \hat{b}_q^\dagger \hat{b}_q \) are the occupation numbers of quasiparticles and phonons, correspondingly, and \( \varepsilon_k \) and \( \tilde{\varepsilon}_q \) are the dispersion relations of quasiparticles and phonons. We use the matrix elements of electron-electron and electron-phonon interactions \( U_0 \) and \( M_0 \) independent of momentum, as the specific form of the interaction terms is not critical for the behaviour studied in this work. We also assume the laser radiation uniform, to make the work values coordinate-independent.

Using the gauge in which the parameters \( u_k, v_k \) are real-valued, and the fact \( u_k = u_{-k}, v_k = v_{-k} \), we convert the last term in (7) to the quasiparticle basis:

\[ \hat{H}_{e-ph} = M_0 \sum_{kq} \left[ \hat{b}_q^\dagger \hat{\gamma}_{k+q,\sigma}^\dagger (u_k u_{k+q} - v_k v_{k+q}) \right. + \hat{b}_q \hat{\gamma}_{k+q,\sigma} (u_k u_{k+q} - v_k v_{k+q}) + \hat{b}_q \hat{\gamma}_{k+q,\sigma}^\dagger (u_k u_{k+q} + v_k u_{k+q}) \]

\[ + \left. \hat{b}_q^\dagger \hat{\gamma}_{-k+q,\sigma}^\dagger (u_k v_{k-q} + v_k u_{k-q}) \right] + H.c. \]

The first two lines correspond to the scattering of the quasiparticle creating the phonon, the third line describes the recombination of two quasiparticles creating the phonon, while the fourth gives the obviously unphysical process of three-particle creation without energy conservation. It is useful to introduce the coefficients for the scattering and recombination processes:

\[ S_{kq} = M_0 (u_k u_{k+q} - v_k v_{k+q}), \]

\[ R_{kq} = M_0 (u_k v_{k-q} + v_k u_{k-q}). \]

The system of kinetic equations [26] writes as:

\[ \frac{dn_{k\sigma}}{dt} = -\frac{n_{k\sigma}}{\tau_e} + G_{k\sigma} - R_{k\sigma} + J_{k\sigma}^{(e-e)} + J_{k\sigma}^{(S)} + J_{k\sigma}^{(R)}, \]

\[ \frac{d\tilde{n}_q}{dt} = -\frac{\tilde{n}_q}{\tau_{ph}} + \tilde{J}_q^{(S)} + \tilde{J}_q^{(R)}. \]

The lifetimes \( \tau_e, \tau_{ph} \) of nonequilibrium quasiparticles and phonons correspond to leaving the excited area.

The optical generation and recombination rates \( G, R \) describing the creation or annihilation of two quasiparticles with momenta \( k, -k \) are proportional to the radiation
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Intensity at the corresponding frequency $\omega$ and depend on the particle occupations:

$$G_{k\sigma} = \alpha I \left( \frac{2\varepsilon_k}{\hbar} \right) (1 - n_{k\sigma})(1 - n_{-k,-\sigma}),$$  \hspace{1cm} (13)

$$R_{k\sigma} = \alpha I \left( \frac{2\varepsilon_k}{\hbar} \right) n_{k\sigma} n_{-k,-\sigma},$$  \hspace{1cm} (14)

where $I(\omega)$ is the intensity and $\alpha$ is the prefactor.

The collision integrals for various interaction terms have the form [27]:

$$J_{k\sigma}^{(e-e)} = \frac{2\pi}{\hbar} U_m^2 \sum_{pmr} [(1 - n_{k\sigma})(1 - n_{p,-\sigma}) n_{m,-\sigma} n_{r\sigma}$$

$$- n_{k\sigma} n_{p,-\sigma} (1 - n_{m,-\sigma})(1 - n_{r\sigma})] F(\Delta\varepsilon) \delta_{k+p,m+r},$$  \hspace{1cm} (15)

$$J_{k\sigma}^{(S)} = \frac{2\pi}{\hbar} \sum_q |S_{kq}|^2 [(1 - n_{k\sigma}) n_{k-q,\sigma} \tilde{\sigma}_q F(\varepsilon_k - \varepsilon_{k-q} - \tilde{\sigma}_q)$$

$$+ (1 - n_{k\sigma}) n_{k+q,\sigma} (\tilde{\sigma}_q + 1) F(\varepsilon_k - \varepsilon_{k+q} + \tilde{\sigma}_q)$$

$$- n_{k\sigma} (1 - n_{k-q,\sigma}) (\tilde{\sigma}_q + 1) F(\varepsilon_k - \varepsilon_{k-q} - \tilde{\sigma}_q)$$

$$- n_{k\sigma} (1 - n_{k+q,\sigma}) \tilde{\sigma}_q F(\varepsilon_k - \varepsilon_{k+q} + \tilde{\sigma}_q)]$$

$$J_{k\sigma}^{(R)} = \frac{2\pi}{\hbar} \sum_q |R_{kq}|^2 [(1 - n_{k\sigma})(1 - n_{q-k,\sigma}) \tilde{\sigma}_q$$

$$- n_{k\sigma} n_{q-k,\sigma} (\tilde{\sigma}_q + 1)] F(\varepsilon_k + \varepsilon_{q-k} - \tilde{\sigma}_q)$$  \hspace{1cm} (16)

for quasiparticles,

$$J_{k}^{(S)} = \frac{2\pi}{\hbar} \sum_{k\sigma} |S_{kq}|^2 [(1 - n_{k\sigma}) m_{k+q,\sigma} (\tilde{\sigma}_q + 1) F(\varepsilon_k - \varepsilon_{k+q} + \tilde{\sigma}_q)$$

$$- (1 - n_{k\sigma}) n_{k-q,\sigma} \tilde{\sigma}_q F(\varepsilon_k - \varepsilon_{k-q} - \tilde{\sigma}_q)]$$  \hspace{1cm} (17)

$$J_{k}^{(R)} = \frac{2\pi}{\hbar} \sum_{k} |R_{kq}|^2 F(\varepsilon_k + \varepsilon_{q-k} - \tilde{\sigma}_q)$$

$$\times [n_{k\sigma} n_{q-k,\sigma} (\tilde{\sigma}_q + 1) - (1 - n_{k\sigma})(1 - n_{q-k,\sigma}) \tilde{\sigma}_q]$$  \hspace{1cm} (18)

and phonons, correspondingly, and the factor $F(\Delta\varepsilon)$ was introduced to account the broadening of energy levels.

3. Numerical simulation

In the simulation, the following parameter values were used: Debye temperature $T_D \approx 350$ K ($k_BT_D = \hbar\omega_D = 0.03$ eV), Fermi energy $E_F = 3$ eV, Fermi wave number $k_F = 0.75k_{\text{max}}$, where $k_{\text{max}} = \pi/a$ is the boundary of the 1st Brillouin zone. Initial value of the energy gap $\Delta(t=0) = 10^{-3}$ eV~$k_BT_c$. The values belong to the range typical to superconductors: e.g. Nb ($T_D = 275$ K, $E_F = 6.5$ eV, $T_c = 9.2$ K), Nb$_3$Sn [29] ($T_D = 300$ K, $E_F = 10.5$ eV, $T_c = 18.9$ K), La-Sr-Cu-O [30] ($T_D = 310\ldots370$ K, $E_F = 0.1$ eV, $T_c \approx 40$ K).

Worthy to note that the specific numbers are not essential for the phenomena under study as far as the main relation $\Delta \ll \hbar\omega_D \ll E_F$ is satisfied.

The value of matrix element $V_0$ is calculated following the BCS equation [11]. The matrix element of electron-phonon interaction $M_0$ is derived from the time between
electron-lattice collisions $\tau \sim h/2\pi M_0^2$ which for the typical metal at the temperature $T \sim 1$ K can be estimated $\sim 10^{-11}$ s. The matrix element of electron-electron interaction $U_0$ was taken equal to $M_0$. As the ratio between electron-electron and electron-phonon interaction constants for different superconducting materials varies widely [12] [13], the value $C \approx 1$ can be considered realistic.

The time of electron-electron scattering, however, not only is determined by the material parameters but also depends nonlinearly on the carrier density. As a result, it can be as large as picoseconds [31] [32] and as low as attoseconds [33] for different materials. For the problem considered in this work, the value of electron-electron scattering time is determined by the density of quasiparticles corresponding to the absorbed laser energy.

The intensity of optical radiation $I$ is measured in units giving the coefficient $\alpha = 1$ in equations (13), (14) i.e. in number of quanta absorbed, and its time dependence is approximated by Gaussian function $\sim \exp\left(-t^2/2\sigma^2\right)$ with duration given by $\sigma$. We assume that the laser pulse uniformly illuminates the whole area of consideration with linear size $10 \mu m$. Then, using the values of Fermi velocity $\sim 10^6$ m/s and sound velocity $\sim 10^3$ m/s, we can estimate the lifetimes of quasiparticles and phonons as the times of leaving the system $\tau_e = 10^{-11}$ s and $\tau_{ph} = 10^{-8}$ s, correspondingly.

In our study, we consider the temperature low enough for the equilibrium densities of quasiparticles and phonons to be zero. With the nonequilibrium quasiparticles present, the value of order parameter $\Delta$ decreases following the equation (1). The simulation of the kinetic equations (11)–(19) is performed on the momentum lattice $32 \times 32 \times 32$ which can be considered large enough to describe the macroscopic behaviour. The discreteness of the energy spectrum in the system is compensated with broadening of the energy levels $\Delta\varepsilon \sim 10^{-3}$ eV and choosing wider spectral line of laser radiation $\hbar\Delta\omega = 0.1$ eV. The laser line shape and level broadening factor $F(\Delta\varepsilon)$ are taken in the form of Gaussian functions. The numerical method used for the simulation of kinetic equations is described in details in [28].

4. Superconductivity suppression with laser pulse

In figures 1 and 2 we show the simulation results demonstrating the system behaviour under the action of laser pulse.

In the case of shorter femtosecond pulse (figure 1), the complete suppression of the superconductivity is delayed in relation to the pulse action, approximately at 0.3 ps for the chosen problem parameters. It is caused by the finite time needed for the high-energy quasiparticles to arrive near the Fermi surface due to relaxation. In the case of longer picosecond pulse (figure 2), the suppression takes approximately 1 ps and the further energy absorption results only in the generation of additional phonons.

The energy of optical quantum $\hbar\omega$ affects the time of switching and the maximal number of quasiparticles only marginally. On the other hand, higher values of the radiation quantum energy delay the start of the order parameter decreasing (figure
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Figure 1. Results of simulation for several energies of optical quantum $\hbar \omega = 0.2, 0.5, 0.8, 3.0$ eV, in the case of femtosecond pulse ($\sigma = 10$ fs, $I = 1.0$), with (a) order parameter $\Delta$, (b) average energy of quasiparticles, (c) number of quasiparticles and (d) phonons.

It can be explained by the time required for the quasiparticles to reach low enough energies.

The effect of the higher intensity consists in the quicker suppression of superconductivity. In figure 2, we present the results of calculation for the picosecond laser pulse of various intensities. We should note that for sufficiently large intensities, the profiles of the order parameter dropping are similar due to nonlinear dependence of the relaxation rate on the particle density.

Summarizing, the superconductivity suppression in the discussed conditions is related to several causes. During the action of laser pulse, the order parameter is depleted due to energy absorption. After that, the relaxation of the excess high-energy quasiparticles increases occupations $n_{k\uparrow}$, $n_{k\downarrow}$ at energies lower than Debye energy which enter the BCS equation (1) and decrease the energy gap.

At large enough energy of the pulse, the superconductivity can be switched off completely, even during the time of laser pulse (figure 2). This case, though, can lead to harmful side effects due to the excess heat emission, and slow down the backwards
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Figure 2. Same as figure 1 for the picosecond pulse (\(\sigma=1\) ps, \(I=2.5\times10^{-3}\)).

Figure 3. Suppression of the superconducting order parameter with picosecond pulse (\(\sigma=1\) ps, \(\hbar \omega=0.2\) eV), calculated for several intensities \(I\).

switching. It makes preferable to choose the case of lower energy impact with delayed order parameter suppression. Next we study the possibility to accelerate this stage of the process.
5. Effect of transport current

The process of superconductivity suppression after the action of ultrashort laser pulse can be affected by the transport current in two different ways. First, the initial value of order parameter before the impact is lowered, decreasing the energy needed to suppress the superconducting state which can potentially provide the faster switching. On the other hand, with the lower density of Cooper pairs affecting the efficiency of the laser radiation absorption, the decreased amount of quasiparticles is generated, resulting in slower relaxation and delaying the suppression of the order parameter. The relative contributions of these factors depend on the radiation frequency which determines the energy of the generated quasiparticles.

In the presence of transport current, the Cooper pairs have momentum \(2\hbar k_s\), i.e. consist of electrons with momenta \(\hbar(k_s + k)\) and \(\hbar(k_s - k)\). The unitary transformation coefficients and the order parameter obtain the complex factor [34]:

\[
\Delta(r) = \Delta^{(0)} e^{i2k_s r},
\]

\[
u_k(r) = u_k^{(0)} e^{ik_s r},
\]

\[
u_k(r) = v_k^{(0)} e^{ik_s r}.
\]

We can neglect the phase change over the linear size \(L\) of the volume under consideration if the current is small enough, so that \(k_s L \ll 2\pi\), i.e. \(k_s \ll 2\pi/L \ll k_F\).

In this case the relations (2)—(5) remain unchanged with equations (1), (4), (13), (14) modified to use the corresponding momenta and particle numbers:

\[
\Delta = U_0 \sum' u_k v_k (1 - n_{k_s + k, \uparrow} - n_{k_s - k, \downarrow}),
\]

\[\xi_k = \frac{1}{2} \left( \frac{\hbar^2(k_s + k)^2}{2m} + \frac{\hbar^2(k_s - k)^2}{2m} \right) - E_F,\]

\[G_{k_s + k, \sigma} = \alpha I \left( \frac{\epsilon_{k_s + k} + \epsilon_{k_s - k}}{\hbar} \right) (1 - n_{k_s + k, \sigma})(1 - n_{k_s - k, -\sigma}),\]

\[R_{k_s + k, \sigma} = \alpha I \left( \frac{\epsilon_{k_s + k} + \epsilon_{k_s - k}}{\hbar} \right) n_{k_s + k, \sigma} n_{k_s - k, -\sigma}.
\]

The current in the superconductor is the sum of contributions from all electrons:

\[
J = \frac{e\hbar}{m} \langle \text{BCS} \sum_{k\sigma} \hat{a}_{k\sigma}^{\dagger} \hat{a}_{k\sigma} \rangle_{\text{BCS}}\]

(24)

This expression can be re-written as [35]:

\[
J = \frac{e\hbar}{m} \sum_k (k_s + k) \left[ |u_k|^2 n_{k_s + k} + |v_k|^2 (2 - n_{k_s - k}) \right],
\]

(25)

where \(n_k = \langle \text{BCS} \sum_{\sigma} \hat{a}_{k\sigma}^{\dagger} \hat{a}_{k\sigma} \rangle_{\text{BCS}}\) is the number of quasiparticles with momentum \(k\) and the summation in (25) goes over all momentum states in the Brillouin zone.

During the simulation, the kinetic equations (11)—(19) are solved numerically along with equations (20)—(25) to update the superconducting order parameter and
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Figure 4. Time evolution of order parameter (a,d), number of quasiparticles (b,e) and phonons (c,f) in the superconductor, after the action of femtosecond pulse ($\sigma=10$ fs, $I=1.0$), calculated for several values of current density $j=0\pm8.8\cdot10^3$ A/cm$^2$, at two values of radiation quantum energy $\hbar\omega=0.2$ eV (a-c) and 3.0 eV (d-f).

the momentum of Cooper pairs, taking into account the occupations of low-energy quasiparticle levels.
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Figure 5. Time needed for the complete suppression of superconductivity depending on the current density, calculated for several energies of the radiation quantum. Intensity $I=1.0$. The missing points at low current densities correspond to the cases when the complete suppression of order parameter was not achieved.

In figures 4(a)—4(f) we show the process of superconductivity suppression in the presence of nonzero current density, calculated for two values of radiation quantum energy. With increasing current density, the initial value of the order parameter decreases. This is the main factor accelerating the suppression of superconductivity at low radiation frequency (figures 4(a)—4(c)). At higher radiation frequency (figures 4(d)—4(f)), however, the stage of the preliminary relaxation of high-energy quasiparticles becomes important (like in figure 1). In this case, the reduction of the generated quasiparticle density due to the transport current can, instead, slow down the superconductivity suppression.

In figure 5 these features are demonstrated by the current dependence of the time needed for the complete suppression of superconductivity, calculated for several quantum energies. We conclude that for achieving the fast suppression of superconductivity with ultrashort laser pulse, a transport current can be beneficial with the appropriate choice of the radiation frequency, and conversely, for a given current density the minimal switching time can be achieved with choosing the optimal laser wavelength. For the parameters used in the simulation, the longer wavelength for large current density and the shorter wavelength for small current density are preferable.

6. Conclusion

In the framework of the problem of ultrafast superconductivity switching with ultrashort laser pulse, we study the relaxation of the nonequilibrium state in the presence of transport current. We use the qualitative theoretical model describing the kinetics of nonequilibrium high-energy quasiparticles and phonons accompanied by the relations of BCS theory for the superconducting state. The process of superconductivity suppression is studied in details using numerical simulation.
While the high enough pulse energy can allow to switch off the superconductivity completely even during the pulse time, it can cause harmful side effects due to excess heat emission, and slow down the backwards switching. In this work, we study the case of lower energy with the delayed suppression of the superconducting order parameter after the action of laser pulse. The delay is caused by the finite time needed for the electron subsystem to lower the average energy due to relaxation, as the order parameter is affected only by the low-energy quasiparticles.

The effect on the superconductivity suppression time caused by the transport current was studied. The results of numerical simulation for various current densities and laser radiation quantum energies demonstrate that the suppression time is determined by two main factors. The first factor is the lowering of the initial value of order parameter due to the presence of transport current, able to speed up the suppression. The second factor is the delay of the first stage of relaxation, depending on the radiation quantum energy. It is found that the optimal current density needed to achieve the minimal switching time, is substantially different for the cases of optical and infrared radiation ranges.

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