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Superradiant dissipative tunneling in a double p–i–n semiconductor heterostructure with thermal injection of electrons

Eliade Stefanescu[a], Werner Scheid[b,*]

[a]*Center of Advanced Studies in Physics at the Institute of Mathematics Simion Stoilow of the Romanian Academy, 13 Calea 13 Septembrie, 76117 Bucharest S5, Romania*

[b]*Institut für Theoretische Physik der Justus-Liebig-Universität, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany*

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Abstract

We propose a semiconductor device with two p–i–n junctions maintained at two different temperatures. When the current injected in the device due to this temperature difference exceeds a threshold value, a superradiant field is created in the first gate that induces an additional current in the second gate. The injection current is amplified by this reaction loop. In this way, the heat flow between the two junctions is partially transformed in superradiant power.

Keywords: Dissipation; Master equation; Fermions; Superradiance; p–i–n structure; Quantum dot

1. Introduction

The superradiance predicted by Dike [1] has been intensively studied [2–4] by taking into account various physical effects as: (1) the statistical distribution of the electron states [5], (2) level degeneracy effects [6,7], (3) Langevin forces acting on the atomic system [8], (4) transverse effects [9], (5) competing of one-photon and three-photon transitions [10], (6) the superradiance spectrum [11], (7) existence of photonic gaps [12–15], (8) spontaneously generated coherence effects [16], (9) superradiance suppression by scattering [17].

However, a new special interest for superradiance is now arising due to the possible applications in the information technology [18], on one hand, and, on the other hand, due to very difficult questions emerging from the dissipative atom–field interaction problem [19–21]. In principle, dissipation is a complex phenomenon with a description depending on the model adopted for the dissipative coupling and on the procedure used for reducing the hamiltonian equation of the system and of the environment to a quantum master equation [22–25].

In this paper, we consider a quantum master equation with microscopic coefficients, that describe the most probable dissipative processes, of single-particle transitions of the system $c_i^+ c_j$ correlated with single-particle

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[*] Corresponding author. Tel.: + 49 641 9933330; fax: + 49 641 9933339.
E-mail address: werner.scheid@theo.physik.uni-giessen.de (W. Scheid).

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transitions of a complex dissipative environment including fermions, bosons, and the electromagnetic field. This equation [26–28] is

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = -\frac{i}{\hbar}[H,\rho(t)] + \sum_{i,j=1}^{N} \lambda_{ij}([c_i^+ c_j \rho(t), c_j^+ c_i] + [c_i^+ c_j, \rho(t) c_j^+ c_i]) \tag{1}$$

with the hamiltonian of the dissipative system

$$H = H_0 + V^R, \tag{2}$$

$$H_0 = \sum_i \varepsilon_i c_i^+ c_i, \tag{3}$$

$$V^R = \frac{1}{4}\sum_{ijkl} \langle ij|V^R|kl\rangle c_i^+ c_j^+ c_l c_k, \tag{4}$$

where V^R is the residual two-body potential, and N^2-1 explicit dissipative coefficients for an N-level system

$$\lambda_{ij} = \lambda_{ij}^F + \lambda_{ij}^B + \gamma_{ij}. \tag{5}$$

The coefficients depend on the dissipative two-body potentials V^F, V^B, the densities of the environment states g_α^F, g_α^B, the occupation probabilities of these states f_α^F, f_α^B, and the temperature T, that are in agreement with the detailed balance principle [29]. For a rather low temperature, $T \ll \varepsilon_{ji} = \varepsilon_j - \varepsilon_i$, $j > i$, these terms are

$$\lambda_{ij}^F = \frac{\pi}{\hbar}|\langle\alpha i|V^F|\beta j\rangle|^2[1 - f_\alpha^F(\varepsilon_{ji})]g_\alpha^F(\varepsilon_{ji}), \tag{6a}$$

$$\lambda_{ji}^F = \frac{\pi}{\hbar}|\langle\alpha i|V^F|\beta j\rangle|^2 f_\alpha^F(\varepsilon_{ji}) g_\alpha^F(\varepsilon_{ji}) \tag{6b}$$

for the Fermi environment,

$$\lambda_{ij}^B = \frac{\pi}{\hbar}|\langle\alpha i|V^B|\beta j\rangle|^2[1 + f_\alpha^B(\varepsilon_{ji})]g_\alpha^B(\varepsilon_{ji}), \tag{7a}$$

$$\lambda_{ji}^B = \frac{\pi}{\hbar}|\langle\alpha i|V^B|\beta j\rangle|^2 f_\alpha^B(\varepsilon_{ji}) g_\alpha^B(\varepsilon_{ji}) \tag{7b}$$

for the Bose environment, and

$$\gamma_{ij} = \frac{2\alpha}{c^2\hbar^3}\,\vec{r}_{ij}^{\,2}\varepsilon_{ji}^3\left(1 + \frac{1}{\mathrm{e}^{\varepsilon_{ji}/T} - 1}\right) \tag{8}$$

for the free electromagnetic field, where $\vec{r}_{ij}$ is the dipole moment and $\alpha = \mathrm{e}^2/(4\pi\varepsilon\hbar c) \approx \frac{1}{137}$.

2. The superradiant double p–i–n structure

To illustrate the applicability of this description of dissipative processes, we consider a semiconductor array of quantum systems as represented in Fig. 1. A transition $|1\rangle \rightarrow |0\rangle$ of an active electron is coupled to a single-particle transition in the sea of the conduction electrons, and this coupling strongly depends on the two separation barriers between the two conduction regions and the quantum wells with two states $|1\rangle$ and $|0\rangle$. Of course, these barriers must have heights significantly higher than the thermal excitation energy, that we take for the room temperature $E_{th} \approx 0.025\,\mathrm{eV}$. The penetrabilities do not exceed values leading to an injection current by tunneling. For the cases considered in the following application, these penetrabilities can reach values of $P = 10^{-5}$, that provide a strong separation of the active electrons from the conduction electrons. When such barriers do not exist, the wave-function $\psi_i(\vec{r})$ of an active electron and $\Phi_\alpha(\vec{R})$ of a dissipative electron are quasi-superposed, and the matrix elements $\langle\alpha i|V^F|\beta j\rangle$ for a Coulomb near-field potential $V^F = \alpha\hbar c/|\vec{R} - \vec{r}|$ are rather large, leading to a strong dissipative coupling. With these barriers, the two wave