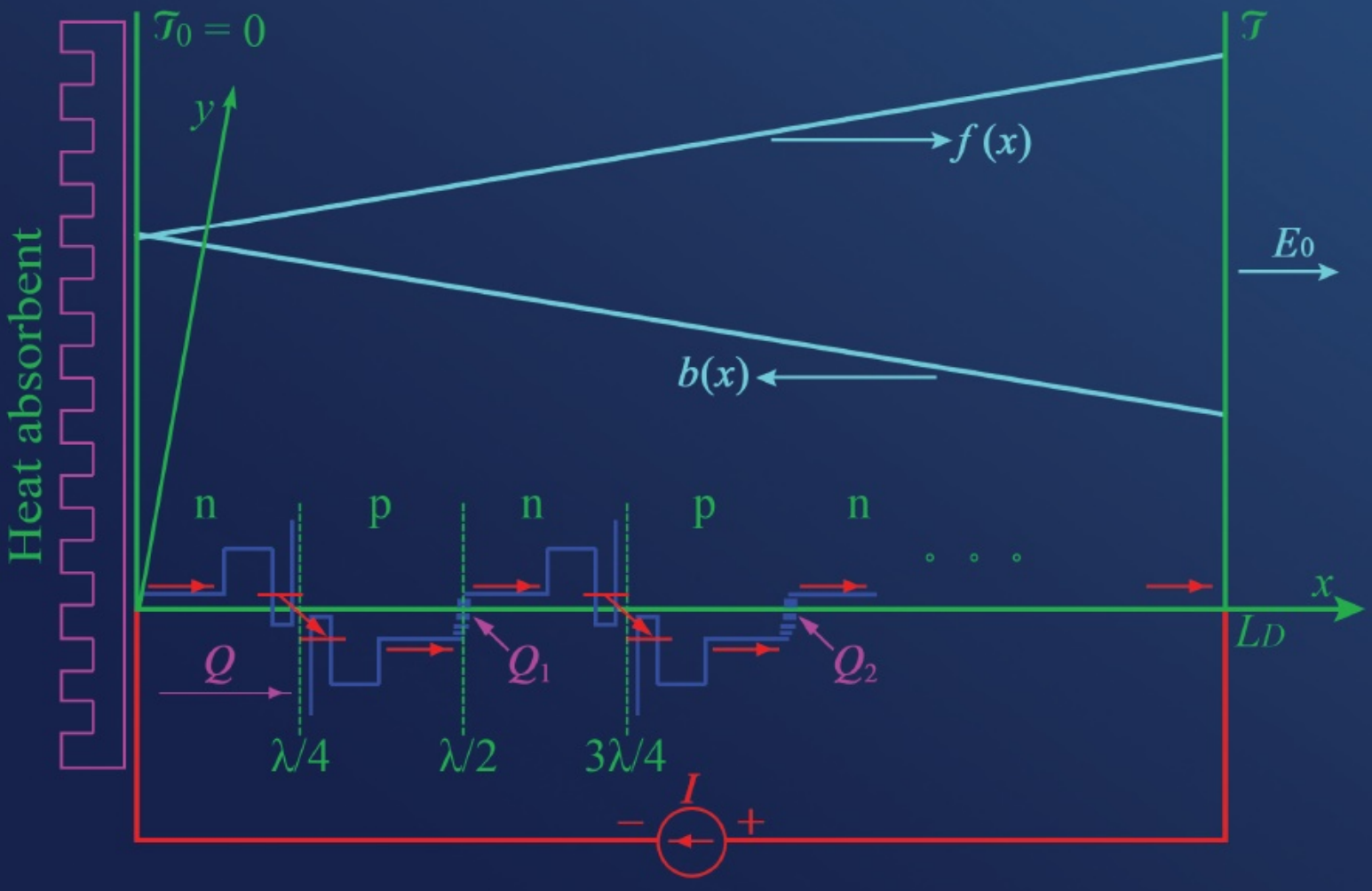
eISBN: 978-1-68108-419-0
ISBN: 978-1-68108-420-6

eISSN: 2542-5072
ISSN: 2542-5064

Open Quantum Physics and Environmental Heat Conversion into Usable Energy [Volume 2]



Eliade Stefanescu

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Open Quantum Physics and Environmental Heat Conversion into Usable Energy

(Volume 2)

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Volume # 2

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eISSN (Online): 2542-5072

ISSN (Print): 2542-5064

eISBN (Online): 978-1-68108-419-0

ISBN (Print): 978-1-68108-420-6

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PREFACE

In the first volume of this book, I presented basic ideas of the open quantum physics, and an application of this theory based on the description of a remarkable phenomenon/device, for the energy production on account of the environmental heat. Evidently, the first basic idea is the quantum mechanics itself, and the second is the electromagnetic theory. As it is customary in literature, the basic theories of these fields have been presented on two separate bases, of quantum mechanics, and of the Maxwell theory, which do not form a self-consistent foundation for the interaction of a particle with the electromagnetic field, and, generally, for the relativistic dynamics of a quantum particle. However, on the occasion of these investigations, I found that, in fact, quantum mechanics includes the relativistic dynamics of a quantum particle, when a bound spectrum is considered for such a particle in an inertial frame of reference. More than that, for our application, consisting of a system of quantum injection dots in a semiconductor structure interacting with an electromagnetic field in a Fabry-Perot cavity, other basic aspects had also been missed in the first volume: the effects of the crystal lattice on the quantum dot dynamics, and a microscopic description of the specific semiconductor structures.

A second volume seemed to be necessary for the integrity of this book. In this volume, we provide a self-consistent foundation for the description of the electron-field interaction, for the basic elements involved in our application, and for the dissipative couplings of the active elements, the quantum injection dot electrons and the coherent electromagnetic field, with the conduction electrons and the vibrations of the crystal lattice. These phenomena are specific to open quantum physics, a theoretical field lately describing the dissipative dynamics as a dynamic semigroup. However, in this study, we use a method of Ford, Lewis, and O'Connell, providing an analytic, microscopic description of the systems of interest. We consider the structural characteristics, as the electron wave functions, the dipole moments, the electron-field coupling coefficients, and the energy and polarization decay coefficients for the active electron couplings to the crystal lattice vibrations, and to the conduction electrons and holes. We calculate the operational characteristics of the devices, as the intensity of the electromagnetic field which propagates through a superradiant or an injection structure, and the injection currents in such a structure. These quantities depend on a large number of physical constants, and material properties, such as the effective masses of the electrons and holes, the mobilities of these particles in the semiconductor crystal, the atomic masses, the elasticity coefficients, the impurity concentrations, and the geometric parameters. For a better understanding of the physical models, I give a large number of explicit numerical calculations, with results which can be compared to well-known experimental data.

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ACKNOWLEDGEMENTS

The author is grateful to Professor R. F. O'Connell from Louisiana State University, for providing a microscopic method for reducing the quantum dynamics to a quantum master equation, without altering the quantum-mechanical principles, and a Hamiltonian for the electron interaction with the angular momentum of the electromagnetic field.

CONFLICT OF INTEREST

The author declares that he has no affiliation with any organization or entity from financial point of view in the subject matter or materials discussed in this eBook.

CHAPTER 1

Introduction

Abstract: While in the first volume of this book we presented a set of methods for the description of the open systems, and applications to a superradiant semiconductor structure, in this volume we concentrate on the microscopic theory and a detailed investigation of the heat conversion into usable energy. Our study is essentially based on master equations with explicit microscopic coefficients, for the active electrons, superradiant field, and crystal lattice vibrations. The quantum dynamics of electrons and electromagnetic field is obtained in the framework of a unified relativistic quantum theory, from the description of a quantum particle as a vibration propagating in space, and a relativistic principle asserting a limitation of the wave function spectrum for a finite velocity c, which does not depend on the frame of reference. The electron dynamics is described in the periodic potential of a crystal lattice and an internal field induced by impurity doping, thermal vibrations, or the application of external fields. The dissipative processes are described as resonant phenomena, with energy conservation, of correlated transitions of particles in the systems of interest with other particles of the crystal. We investigate the operation characteristics for the two versions of the device, the longitudinal quantum heat converter, and the transversal one, and the corresponding structures for the conversion of electromagnetic energy into electric energy.

Keywords: Affinity, Bipolar transistor, Bose-Einstein statistics, Coherent field, Conduction band, Correlated transitions, Creation-annihilation operators, Decay, Dissipation, Electron, Fermi-Dirac statistics, Fermionic operators, Forbidden band, Hamiltonian, Internal field, Lindbladian, Optical phonon, Photon, Semiconductor junction, Semiconductor structure, Superradiant transistor, Valence band.

In the first volume of this book [1], we presented important physical and mathematical ideas of open quantum physics [2 - 9], issued for an adequate description of the realistic physical systems involved in the new technological developments, as the semiconductor optoelectronic nanostructures [10 - 13]. These ideas mainly refer to the atom-field interaction [14 - 16] and the couplings of the systems of interest to the dissipative neighboring systems [17 - 19], mainly contained in their physical support. The dynamics of a system of interest in a

dissipative environment is a multidisciplinary problem, including basic elements of classical and modern fields, which are still under investigation [20 - 25], such as quantum mechanics [26 - 32], electromagnetism [33 - 35], quantum optics [36 - 39], non-equilibrium thermodynamics [40 - 42], statistical mechanics [43 - 47], and stochastic physics [48 - 50].

The starting point of our research was Lindblad's axiomatic theory of the dissipative coupling [51], and the method of Sandulescu and Scutaru for reducing Lindblad's description of the dissipative dynamics by semigroups, to the well-known phenomenological processes of quantum friction and diffusion [52]. This is a description of the quantum dynamics, obtained from Lindblad's master equation of a system with the density matrix $\rho(t)$ and the Hamiltonian H,

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = -\frac{\mathrm{i}}{\hbar}[H,\rho(t)] + \frac{1}{2\hbar}\sum_n \left\{[V_n\rho(t),V_n^+] + [V_n\rho(t),V_n^+]\right\} \ , \qquad \textbf{(1.1)}$$

which includes a dissipation term with the openness operators

$$V_n = \sum_m a_{nm}A_m \ . \qquad \textbf{(1.2)}$$

These operators are linear combinations of the system operators A_n with unspecified complex coefficients a_{nm}. This form of the dissipation term, valid for the most cases of practical interest of the weak dissipative coupling, guarantees the positivity of the density matrix during the whole evolution of the system. Our first objective was to investigate the physical effects of the dissipation terms on two basic quantum phenomena: (1) quantum tunneling, and (2) the atom-field interaction. In this way, we found two interesting effects: (1) tunneling enhancement, due to the additional transitions stimulated by environment [53 - 60], and (2) coupling through environment of the atomic operators, leading to a possible absorption of the environmental energy by a coherent electromagnetic field propagating through this environment [61].

Although Lindblad's master equation (1.1) is in agreement with the quantum principles, and provides interesting informations about the dissipative dynamics, this equation is still unsatisfactory, including a number of unspecified parameters a_{nm}. The difficulties encountered in the application of this equation to a harmonic oscillator by considering the openness with the two operators x and p of this system have been subjects of contradictory discussions [62 - 68]. In principle, from physical point of view, the openness of a harmonic oscillator with x and p is

not understandable, since, as one can see from subsection 2.1.8 in [1], *x* and *p* of a harmonic oscillator represent the same operator at two different moments of time, for a phase difference *π/2* in the Heisenberg representation. This phase difference is not significant in this problem where the dissipative processes, as damping and diffusion, are described as slow processes in comparison with the Hamiltonian oscillations of this system. For an openness with *x* and *p*, from equation (1.1) for a harmonic oscillator with the Hamiltonian *H*, the mass *M*, and a resonance frequency ω_0, at a temperature *T*, one can obtain the quantum master equation [69]:

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = -\frac{\mathrm{i}}{\hbar}[H,\rho(t)] - \frac{\lambda}{2\hbar}\Big\{\mathrm{i}\Big([q,p\rho(t)+\rho(t)p]-[p,q\rho(t)+\rho(t)q]\Big) + \coth\frac{\hbar\omega_0}{2T}\Big(M\omega_0[q,[q,\rho(t)]]+\frac{1}{M\omega_0}[p,[p,\rho(t)]]\Big)\Big\}. \quad \textbf{(1.3)}$$

We obtain equations for the diagonal elements,

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{nn}(t) = \lambda\Big\{(n+1)\left[\left(\coth\frac{\hbar\omega_0}{2T}+1\right)\rho_{n+1,n+1}(t)-\left(\coth\frac{\hbar\omega_0}{2T}-1\right)\rho_{nn}(t)\right] + n\left[\left(\coth\frac{\hbar\omega_0}{2T}-1\right)\rho_{n-1,n-1}(t)-\left(\coth\frac{\hbar\omega_0}{2T}+1\right)\rho_{nn}(t)\right]\Big\}, \quad \textbf{(1.4)}$$

which are physically comprehensible, being in agreement with the Pauli master equation (subsection 3.2.1 in [1]) and detailed balance relations:

$$\frac{\rho_{n+1,n+1}(\infty)}{\rho_{nn}(\infty)} = \frac{\rho_{nn}(\infty)}{\rho_{n-1,n-1}(\infty)} = e^{-\hbar\omega_0/T}\ . \quad \textbf{(1.5)}$$

However, equations for the non-diagonal elements are

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{mn}(t) = -\mathrm{i}(m-n)\omega_0\rho_{mn}(t) - \lambda\Big\{\left[(m+n+1)\coth\frac{\hbar\omega_0}{2T}-1\right]\rho_{mn}(t) - \sqrt{(m+1)(n+1)}\left[\coth\frac{\hbar\omega_0}{2T}+1\right]\rho_{m+1,n+1}(t) - \sqrt{mn}\left[\coth\frac{\hbar\omega_0}{2T}-1\right]\rho_{m-1,n-1}(t)\Big\}\ . \quad \textbf{(1.6)}$$

Besides the Hamiltonian and the decay terms, two coupling terms of the

CHAPTER 2

Unitary Relativistic Quantum Dynamics and Electromagnetic Field

Abstract: In this chapter, we consider a quantum particle wave function with a bound spectrum of velocity c, and obtain the relativistic momentum based on the group velocity of this wave function. With a space-time isometry condition, the Lorentz transformation and the relativistic dynamics were obtained. Considering a field interacting with a quantum particle as a four-vector conjugated to the space-time vector in the time-dependent phase, we obtain the Lorenz force and the Maxwell equations. It is interesting that only the Ampère-Maxwell equation of a magnetic circuit is specific to the electromagnetic field, while the other equations are general for a field interacting with a charged quantum particle. Considering the time-dependent phase of a quantum particle interacting with an electromagnetic field with a space-time homogeneity condition, we obtain Lorentz transformations for this field. For a quantum particle at a non-relativistic velocity, we obtain a wave function with a very rapidly-varying factor, of a frequency proportional to the rest energy of this particle. From the Schrödinger equation of a particle with a relativistic Hamiltonian, we obtain a split of the wave function into four components, describing a proper rotation of this particle with an angular momentum called spin (Dirac's relativistic electron theory). Moreover, we also calculate electron potential in the magnetic field, and two-electron interaction potential.

Keywords: Action, Ampère-Maxwell equation, Angular momentum, Bohr magneton, Dirac matrices, Electric field, Electric potential, Faradey-Maxwell equation, Four-vector, Gauss equation, Giro-magnetic ratio, Group velocity, Hamiltonian, Kinetic energy, Lagrangian, Liénard-Wiechert potentials, Lorentz transformation, Magnetic field, Magnetic moment, Momentum, Pauli matrices, Potential energy, Rest energy, Rest mass, Spin, Vector potential, Wave function, Wave-packet.

2.1. Wave Functions and Relativistic Mechanics

2.1.1. Hamiltonian Equations as Group Velocities

Our world is composed of microscopic particles such as electrons, nucleons and photons [82]. It is remarkable that such a particle is described by a wave function

with a wave vector $\vec{k}$ proportional to the particle momentum $\vec{p} = \hbar\vec{k}$, where $\hbar$ is the Planck's constant [83]. In subsection 2.1.1 of the first volume [1], we described a quantum particle by two wave functions in the two conjugated spaces $\{\vec{r}\}$ and $\{\vec{p}\}$,

$$\psi_0(\vec{r},t) = \frac{1}{(2\pi\hbar)^{3/2}}\int \phi_0(\vec{p},t)e^{\frac{\mathrm{i}}{\hbar}\{\vec{p}\vec{r}-[T(\vec{p})-U(\vec{r})]t\}}\mathrm{d}^3\vec{p} \qquad \textbf{(2.1)}$$

$$\phi_0(\vec{p},t) = \frac{1}{(2\pi\hbar)^{3/2}}\int \psi_0(\vec{r},t)e^{-\frac{\mathrm{i}}{\hbar}\{\vec{p}\vec{r}-[T(\vec{p})-U(\vec{r})]t\}}\mathrm{d}^3\vec{r}\ , \qquad \textbf{(2.2)}$$

with wave packet velocities satisfying the classical dynamics:

$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{r} = \frac{\partial}{\partial\vec{p}}T(\vec{p}) = \frac{\partial}{\partial\vec{p}}H_0(\vec{r},\vec{p}) \qquad \textbf{(2.3a)}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{p} = -\frac{\partial}{\partial\vec{r}}U(\vec{r}) = -\frac{\partial}{\partial\vec{r}}H_0(\vec{r},\vec{p})\ , \qquad \textbf{(2.3b)}$$

where

$$H_0(\vec{r},\vec{p}) = T(\vec{p}) + U(\vec{r}) = E \qquad \textbf{(2.4)}$$

is the Hamiltonian of a non-relativistic particle, with a constant *E* of the particle dynamics, called energy. It is interesting that the particle wave functions (2.1)-(2.2) differ from the Schrödinger wave functions

$$\psi_E(\vec{r},t) = \frac{1}{(2\pi\hbar)^{3/2}}\int \phi_0(\vec{p},t)e^{\frac{\mathrm{i}}{\hbar}\{\vec{p}\vec{r}-Et\}}\mathrm{d}^3\vec{p} \qquad \textbf{(2.5)}$$

$$\phi_0(\vec{p},t) = \frac{1}{(2\pi\hbar)^{3/2}}\int \psi_E(\vec{r},t)e^{-\frac{\mathrm{i}}{\hbar}\{\vec{p}\vec{r}-Et\}}\mathrm{d}^3\vec{r}\ , \qquad \textbf{(2.6)}$$

by a phase factor $e^{-\mathrm{i}2U(\vec{r})t/\hbar}$, which does not alter the densities $|\psi_0(\vec{r},t)|^2$ and $|\phi_0(\vec{p},t)|^2$. We notice that the phase time variation of these wave functions is of a Lagrangian form

$$-\frac{1}{\hbar}Lt = -\frac{1}{\hbar}[T(\vec{p}) - U(\vec{r})]t \ . \tag{2.7}$$

It is interesting that the Hamilton equations (2.3) define the Hamiltonian function (2.4) as a time constant,

$$\frac{\mathrm{d}}{\mathrm{d}t}H_0(\vec{r},\vec{p}) = \frac{\partial H_0}{\partial \vec{r}}\frac{\mathrm{d}\vec{r}}{\mathrm{d}t} + \frac{\partial H_0}{\partial \vec{p}}\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = 0\,, \tag{2.8}$$

called energy:

$$H_0(\vec{r},\vec{p}) = T(\vec{p}) + U(\vec{r}) = E \ . \tag{2.9}$$

We notice that the energy is a conservative function by definition, which means that it cannot be created or destroyed by any process. Any problem of energy creation or destruction is a illogical. The total energy *E* is composed of the kinetic energy $T(\vec{p})$ and the potential energy $U(\vec{r})$.

For a constant potential $U(\vec{r})$, the kinetic energy $T(\vec{p})$ is also constant, and from the first Hamilton equation (2.3a), we obtain a constant group velocity

$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{r} = \frac{\partial}{\partial \vec{p}}T(\vec{p}) = \text{const.}\ , \tag{2.10}$$

in agreement with the first law of the classical mechanics, while, from the second Hamilton equation (2.3b), we obtain a constant momentum $\vec{p}$,

$$\frac{\mathrm{d}}{\mathrm{d}t}\vec{p} = 0 \ . \tag{2.11}$$

This means that this momentum, as the conjugated variable of the coordinate $\vec{r}$ in the particle wave-packets (2.1) and (2.2), depends on the particle velocity:

$$\vec{p} = \vec{p}(\dot{\vec{r}}). \tag{2.12}$$

From (2.3b), we obtain a time variation of the momentum equal to the opposite of the potential gradient called force,

CHAPTER 3

Quantum Systems of Electrons in a Semiconductor Crystal

Abstract: In this chapter, we describe steady states and dynamical characteristics of the electrons in the periodic potential of a crystal, and the application of three semiconductor elements: the rectifying junction, the bipolar transistor, and the superradiant junction. While for an arbitrary potential the electron momentum does not commute with the Hamiltonian, in the periodic potential of a crystal lattice we find a quasi-momentum, which commutes with this Hamiltonian. We obtain the quasi-momentum eigenvalues as eigenvectors of the reciprocal lattice. In this way, we find quasi-momentum eigenstates, called Bloch states, the energy as a function of this quasi-momentum, and equilibrium eigenstates in the quasi-momentum space. From the energy variation with the quasi-momentum in the equilibrium states, we find the tensor of the effective mass of the electron in a crystal lattice. We find that for an internal potential of interaction oriented with the gradient perpendicular to the equilibrium quasi-momentum, the electron dynamics in the semiconductor structure is simply described by the Schrödinger equation of this potential, while the periodic potential of the crystal lattice does not play any role. For N electrons in a quantization volume V, we derive the density of Bloch states as a function of the crystal lattice characteristics. We find the velocity and the acceleration of an electron under the action of an internal potential. Considering a Fermi-Dirac distribution of the Bloch states, we obtain the current density under the action of such a potential. With the statistical distributions and the current densities for electrons and holes, we obtain the electrical characteristics for a semiconductor junction and a bipolar transistor. We consider a superradiant junction, where the electron injection is performed by quantum transitions from an n-region to the p-region in quantum dot arrays. We calculate the wave functions, the electric field, and the potential variation between the two conduction regions, and the dipole moments for two polarizations of the superradiant field: in the direction of the injected current, and in a perpendicular direction to the current.

Keywords: Acceptor, Bipolar transistor, Bloch wave function, Conduction band, Crystal lattice, Direct and indirect gap, Donor, Effective mass, Fermi level, Forbidden band, Heterostructure, Internal field, Perturbation theory, Potential barrier, Quantum well, Quasi-momentum, Reciprocal lattice, Semiconductor junction, Superradiance, Valence band, Wave vector.

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3.1. Semiconductor Structures

3.1.1. Electron States in a Semiconductor Crystal

Semiconductors are very important materials, due to their remarkable electrical and optical properties, the possibilities for varying these characteristics on large scales, and the very interesting micro-systems which can be implemented in their atomic structure [94 - 100]. Generally, a semiconductor material, as silicon with valence *4*, has a diamond crystalline structure (Fig. **3.1**).

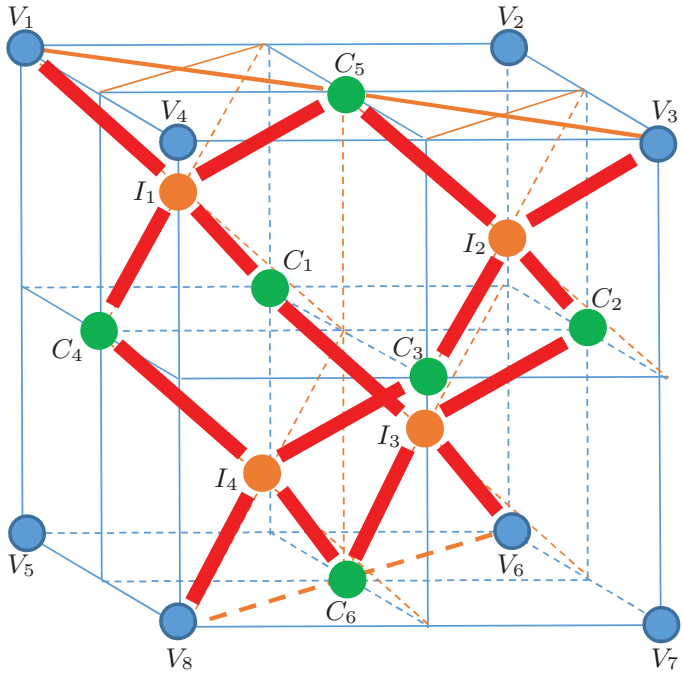

Fig. (3.1). Diamond crystal, as a cubic lattice with centered faces, and *4* inner atoms.

In this figure, a diamond structure is represented as a cubic cell of atoms occupying the 8 vertexes V_1, V_2, V_3, V_4, V_5, V_6, V_7, V_8 the centers C_1, C_2, C_3, C_4, C_5, C_6 of the *6* faces, and *4* inner atoms I_1, I_2, I_3, I_4, oriented in the directions of two diagonals of the two opposite faces V_1V_3 and V_6V_8. We notice that every inner atom (brown) has *4* covalent bonds (red), to the closer vertex atom (blue), and to the atoms in the centers of three faces (green) intersecting at this vertex. Every atom in the center of a face (green) also has *4* covalent bonds, two with closer inner atoms (brown) of this cube, and two with the inner atoms of the adjacent cube. Every vertex atom (blue) has a covalent bond with inner atoms in four from the eight cubes with this vertex. Thus, we find that in this structure every atom has

four covalent bonds. We also notice that this cube contains $6 \cdot \frac{1}{2}$ atoms at the centers of *6* faces, and $8 \cdot \frac{1}{8}$ atoms at the *8* vertexes, making a total of *8* atoms. This is a dense structure, which suggests small potential variations in this structure. It is interesting that this structure is also specific to a $GaAs$–$Al_xGa_{1-x}As$ compound, with *4* heavier *As* atoms per cell in the inner positions I_1-I_4, and *4* lighter *Ga* or *Al* atoms per cell in the outer positions V_1-V_8 and C_1-C_6.

For a rather large crystal, for the atomic potential one may consider the translation symmetry, while the energy levels of the electrons in this potential form a lower valence band and a higher conduction band, separated by a forbidden band (Fig. **3.2**). The forbidden band width $E_g = U_c - U_v$ depends on the chemical composition: for instance, $E_g = 1.426\ eV$ for *GaAs*, ans $E_g = 1.92\ eV$ for $Al_{0.37}Ga_{0.63}As$. Another characteristic of the band structure is the electron affinity E_a, which is the difference between the potential U_0 of the semiconductor surface, and the bottom of the conduction band, $E_a = U_0 - U_c$. For *GaAs*, $E_a = 4.69\ eV$.

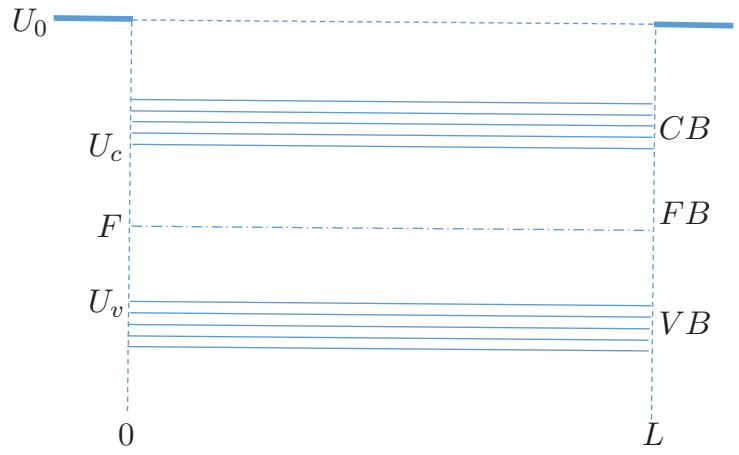

Fig. (3.2). Semiconductor energy band structure: a valence band *VB* with the higher margin U_v, a conduction band *CB* with the lower limit U_c, and a forbidden band *FB* between U_v and U_c, while *F* is the Fermi level determined by the occupation of these bands, and U_0 is the surface potential.

For the dimension L of a semiconductor sample, an uncertainty Δp of the momentum arises according to the uncertainty relation, $\Delta p \cdot L \geq \frac{\hbar}{2}$, which means a width of an energy level

$$\Delta E = \frac{\Delta p^2}{2M} \geq \frac{\hbar^2 c^2}{8L^2 M c^2}\ , \qquad \textbf{(3.1)}$$

CHAPTER 4

Superradiant Structure and Heat Conversion into Usable Energy

Abstract: In this chapter, we derive the operational characteristics of quantum heat converter and a quantum injection device, as functions of the semiconductor structures. We describe the couplings of the active electrons with the superradiant field, the crystal vibrations, and the quasi-free electrons and holes in the conduction regions. The dissipative couplings of the electromagnetic field with the optical vibrations and the quasi-free conduction electrons and holes are taken into consideration according to the results obtained in the first volume. The superradiant power of a quantum heat converter under the action of a current injected in the device, and the electric current generated by a quantum injection device under the action of an incident electromagnetic field are entirely obtained as functions of the physical characteristics and universal constants. We perform numerical calculations for semiconductor structures providing electromagnetic and electric powers of practical interest. Both possible semiconductor configurations, the longitudinal configuration, with the field propagating in the direction of the injected current, and the transversal one, with the field propagating perpendicularly to the injected current, are taken into account.

Keywords: Cavity eigenmode, Commutation relation, Correlated transitions, Coupling coefficient, Creation-annihilation operators, Deep-level path, Elasticity coefficient, Fabry-Perot cavity, Harmonic oscillator, Hermitian matrix, Impurity cluster, Maxwell-Bloch equations, Optical vibration, Polarization, Population, Quantum injection dot, Sound velocity, Superradiant field, Superradiant junction, Vibrational field.

4.1. Couplings of Superradiant Transitions

4.1.1. Continuum Model of Crystal Vibrations

An essential dissipation process of the quantum transitions involves an energy transfer to the crystal lattice vibrations. These vibrations are excited by temperature, and depend on the ion masses and the elastic forces between these ions connected by valence electrons. In a continuum model of the crystal vibrations [103], we describe the displacement field

$$\vec{q}(\vec{r}) \doteq \vec{r}' - \vec{r} \ , \tag{4.1}$$

of a differential element of volume $\mathrm{d}^3\vec{r}$ with the equilibrium position $\vec{r}$, and the expansion of this volume, which, for a small deformation can be considered in a first-order approximation,

$$\begin{aligned}
\mathrm{d}^3\vec{r}' \doteq & \mathrm{d}x'\mathrm{d}y'\mathrm{d}z' = (\mathrm{d}x + \mathrm{d}q_x)(\mathrm{d}y + \mathrm{d}q_y)(\mathrm{d}x + \mathrm{d}q_z) \\
= & (\mathrm{d}x + \frac{\partial q_x}{\partial x_i}\mathrm{d}x_i)(\mathrm{d}y + \frac{\partial q_y}{\partial x_i}\mathrm{d}x_i)(\mathrm{d}x + \frac{\partial q_z}{\partial x_i}\mathrm{d}x_i) \\
= & \mathrm{d}x\mathrm{d}y\mathrm{d}z(1 + \frac{\partial q_x}{\partial x_i}\frac{\mathrm{d}x_i}{\mathrm{d}x})(1 + \frac{\partial q_y}{\partial x_i}\frac{\mathrm{d}x_i}{\mathrm{d}y})(1 + \frac{\partial q_z}{\partial x_i}\frac{\mathrm{d}x_i}{\mathrm{d}z}) \\
= & \mathrm{d}^3\vec{r}\left(1 + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right) \ .
\end{aligned} \tag{4.2}$$

This means that any differential element of length

$$\mathrm{d}l = \sqrt{\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2} \ , \tag{4.3}$$

takes the following form by deformation,

$$\begin{aligned}
\mathrm{d}l' = & \sqrt{\mathrm{d}x'^2 + \mathrm{d}y'^2 + \mathrm{d}z'^2} \\
= & \sqrt{(\mathrm{d}x + \mathrm{d}q_x)^2 + (\mathrm{d}y + \mathrm{d}q_y)^2 + (\mathrm{d}z + \mathrm{d}q_z)^2} \\
= & \sqrt{\mathrm{d}l^2 + 2\mathrm{d}q_i\mathrm{d}x_i + \mathrm{d}q_i\mathrm{d}q_i} \\
= & \sqrt{\mathrm{d}l^2 + 2\frac{\partial q_i}{\partial x_j}\mathrm{d}x_i\mathrm{d}x_j + \frac{\partial q_i}{\partial x_j}\frac{\partial q_i}{\partial x_k}\mathrm{d}x_j\mathrm{d}x_k} \\
= & \sqrt{\mathrm{d}l^2 + \left(\frac{\partial q_i}{\partial x_j} + \frac{\partial q_j}{\partial x_i}\right)\mathrm{d}x_i\mathrm{d}x_j + \frac{\partial q_k}{\partial x_j}\frac{\partial q_k}{\partial x_i}\mathrm{d}x_j\mathrm{d}x_i} \\
= & \sqrt{\mathrm{d}l^2 + 2q_{ij}\mathrm{d}x_i\mathrm{d}x_j} \\
= & \mathrm{d}l\left(1 + q_{ij}\frac{\mathrm{d}x_i}{\mathrm{d}l}\frac{\mathrm{d}x_j}{\mathrm{d}l}\right) \ ,
\end{aligned} \tag{4.4}$$

depending on a deformation tensor

$$q_{ij} = \frac{1}{2}\left(\frac{\partial q_i}{\partial x_j} + \frac{\partial q_j}{\partial x_i} + \frac{\partial q_k}{\partial x_i}\frac{\partial q_k}{\partial x_j}\right) \ , \tag{4.5}$$

which, for small deformations, takes a simpler form

$$q_{ij} = \frac{1}{2}\left(\frac{\partial q_i}{\partial x_j} + \frac{\partial q_j}{\partial x_i}\right) \ . \tag{4.6}$$

It is interesting that in a system of principal axes, when the deformation tensor is diagonal, the expansion of the differential element of the volume (4.2) is a function of the diagonal elements of the deformation tensor (4.6),

$$\mathrm{d}^3\vec{r}' = \mathrm{d}^3\vec{r}\,(1 + q_{xx} + q_{yy} + q_{zz}) \ . \tag{4.7}$$

At the same time, the elongation of a differential element of length,

$$\frac{\mathrm{d}l' - \mathrm{d}l}{\mathrm{d}l} = q_{ij}\frac{\mathrm{d}x_i}{\mathrm{d}l}\frac{\mathrm{d}x_j}{\mathrm{d}l} \tag{4.8}$$

takes the simpler form

$$\frac{\mathrm{d}l' - \mathrm{d}l}{\mathrm{d}l} = q_{xx}\left(\frac{\mathrm{d}x}{\mathrm{d}l}\right)^2 + q_{yy}\left(\frac{\mathrm{d}y}{\mathrm{d}l}\right)^2 + q_{zz}\left(\frac{\mathrm{d}z}{\mathrm{d}l}\right)^2 \ , \tag{4.9}$$

which leads to a simple interpretation of the diagonal elements of the deformation tensor in a system of principal axes, as elongations,

$$q_{xx} = \frac{\mathrm{d}x' - \mathrm{d}x}{\mathrm{d}x} \tag{4.10}$$

$$q_{yy} = \frac{\mathrm{d}y' - \mathrm{d}y}{\mathrm{d}y} \tag{4.11}$$

$$q_{zz} = \frac{\mathrm{d}z' - \mathrm{d}z}{\mathrm{d}z} \ . \tag{4.12}$$

Appendix A

Structure of a Superradiant Junction

The operation of a superradiant junction essentially depends on its structure. We choose a high conductivity n-region, $N_D = 3\times10^{16} \ll N_c = 4.17\times10^{17}cm^{-3}$ (3.148), while the potential (3.465) is

$$U_c = T\ln\frac{N_c}{N_D} = 0.026\ln\left(\frac{4.17\times10^{17}}{3\times10^{16}}\right) = 0.068eV. \tag{A.1}$$

For a positive potential of the higher level well, $U_1 > 0$, from ((782)) we obtain a quantum dot density

$$\begin{aligned} N_e = \frac{M_n T}{\pi\hbar^2}\ln\left(1+e^{-\frac{U_1}{T}}\right) < \frac{M_n c^2 T}{\pi\hbar^2 c^2}\ln 2 = & \quad \frac{0.065\times0.511\times10^6 0.026}{\pi 197^2 nm^2}\ln 2 \\ = & \quad 4.9\times10^{-3}nm^{-2} \\ = & \quad 4.9\times10^{15}m^{-2}. \end{aligned} \tag{A.2}$$

Having in view the effective resonance frequency (4.137), we take two quantum dot energy levels

$$E_1 = U_c - \frac{T}{2} = 0.068 - \frac{0.026}{2} = 0.055eV \tag{A.3}$$

$$E_0 = U_v + \left(\frac{1}{2}+\frac{M_n}{M_p}\right)T. \tag{A.4}$$

In this way, the effective resonance frequency (4.137) achieves the maximum value for a non-absorptive propagation through the conduction regions with a junction transition energy $U_c - U_v$,

$$\hbar\overline{\omega}_0 = E_1 - E_0 + \left(1+\frac{M_n}{M_p}\right)T = U_c - U_v. \tag{A.5}$$

We consider an internal barrier

$$U_0 = 0.200eV \tag{A.6}$$

$$U_{00} = U_g - U_0 = -1.720eV, \tag{A.7}$$

of $Al_xGa_{1-x}As$, with the energy gap $U_g = 1.920eV$, and separation barriers

$$U_B = 0.05eV, \tag{A.8}$$

which means a total height of the higher level potential barrier

$$U_3 = U_c + U_B = 0.068 + 0.05 = 0.118eV. \tag{A.9}$$

We obtain the effective heights of the two barriers,

$$U_0 - E_1 = 0.200 - 0.055 = 0.145eV \tag{A.10}$$

$$U_3 - E_1 = 0.118 - 0.055 = 0.063eV. \tag{A.11}$$

We choose a width $x_0 - x_1 = 10nm$ of this well. From the transcendental equation (4.156) we obtain the ground state energy $E_1 - U_1$ as the limit of a convergent oscillatory sequence

$$\begin{aligned}
(E_1 - U_1)_0 &= \frac{\hbar^2 c^2}{2M_n c^2 (x_0 - x_1)^2} = \frac{197^2 eV^2 nm^2}{2\times 0.065\times 0.511\times 10^6 eV 10^2 nm^2} \\
&= 0.0058421eV \\
(E_1 - U_1)_1 &= (E_1 - U_1)_0 \left(\arctan\sqrt{\frac{U_0 - E_1}{(E_1 - U_1)_0}} + \arctan\sqrt{\frac{U_3 - E_1}{(E_1 - U_1)_0}}\right)^2 \\
&= 0.0058421eV \left(\arctan\sqrt{\frac{0.145}{0.0058421}} + \arctan\sqrt{\frac{0.063}{0.0058421}}\right)^2 \\
&= 0.040961eV \\
(E_1 - U_1)_2 &= (E_1 - U_1)_0 \left(\arctan\sqrt{\frac{U_0 - E_1}{(E_1 - U_1)_1}} + \arctan\sqrt{\frac{U_3 - E_1}{(E_1 - U_1)_1}}\right)^2 \\
&= 0.0058421eV \left(\arctan\sqrt{\frac{0.145}{0.040961}} + \arctan\sqrt{\frac{0.063}{0.040961}}\right)^2 \\
&= 0.022776eV \\
(E_1 - U_1)_3 &= 0.028868eV \\
(E_1 - U_1)_4 &= 0.026426eV \\
(E_1 - U_1)_5 &= 0.027342eV \\
(E_1 - U_1)_6 &= 0.026990eV \\
&\downarrow \\
E_1 - U_1 &= 0.027eV.
\end{aligned} \tag{A.12}$$

With (A.3), we obtain the potential of the higher level well,

$$U_1 = E_1 - (E_1 - U_1) = 0.055 - 0.027 = 0.028eV, \tag{A.13}$$

with the barriers

$$U_0 - U_1 = 0.200 - 0.028 = 0.172eV \tag{A.14}$$

$$U_3 - U_1 = 0.118 - 0.028 = 0.090eV \tag{A.15}$$

and the quantum dot density creating this well,

$$\begin{aligned}
N_e &= \frac{M_n c^2 T}{\pi\hbar^2 c^2} \ln\left(1 + e^{-\frac{U_1}{T}}\right) \\
&= \frac{0.065\times 0.511\times 10^6 0.026}{\pi 197^2 nm^2} \ln\left[1 + \exp\left(-\frac{0.028}{0.026}\right)\right] \\
&= 2.0764\times 10^{-3} nm^{-2} = 2.0764\times 10^{15} m^{-2}.
\end{aligned} \tag{A.16}$$

With this quantum dot density, from (3.471) we obtain the potential of the lower level well,

$$\begin{aligned} U_2 = \quad & T\ln\left[\exp\left(\frac{\pi\hbar^2c^2N_e}{M_pc^2T}\right)-1\right] \\ = \quad & 0.026\ln\left[\exp\left(\frac{\pi 197^2 2.0764\times10^{-3}}{0.5\times0.511\times10^6 0.026}\right)-1\right] \\ = \quad & -0.084453 \approx -0.084eV. \end{aligned} \tag{A.17}$$

Choosing a potential of the lower level well separation barrier

$$U_4 = U_v - 0.05\text{e}V, \tag{A.18}$$

from (A.4) we find the effective height of the lower level well separation barrier

$$\begin{aligned} E_0 - U_4 = \quad & U_v + \left(\frac{1}{2}+\frac{M_n}{M_p}\right)T - (U_v - 0.05) = 0.05 + \left(\frac{1}{2}+\frac{M_n}{M_p}\right)T \\ = \quad & 0.05 + \left(\frac{1}{2}+\frac{0.065}{0.5}\right)0.026 = 0.066380 \approx 0.066eV, \end{aligned} \tag{A.19}$$

while, neglecting the thin layer effect (subsection 3.3.4),

$$U_2 - U_{00} = -0.084 + 1.720 = 1.636eV. \tag{A.20}$$

From (4.157) we calculate the ground state energy of the lower level potential, by determining the width of this potential $x_4 - x_2 = 3nm$,

$$\begin{aligned} (U_2 - E_0)_0 = \quad & \frac{\hbar^2c^2}{2M_pc^2(x_4-x_2)^2} = \frac{197^2eV^2nm^2}{2\times0.5\times0.511\times10^6eV3^2nm^2} \\ = \quad & 0.0084386eV \\ (U_2 - E_0)_1 = \quad & (U_2 - E_0)_0\left(\arctan\sqrt{\frac{U_2-U_{00}}{(U_2-E_0)_0}-1}+\arctan\sqrt{\frac{E_0-U_4}{(U_2-E_0)_0}}\right)^2 \\ = \quad & 0.0084386eV\left(\arctan\sqrt{\frac{1.636}{0.0084386}-1}+\arctan\sqrt{\frac{0.066}{0.0084386}}\right)^2 \\ = \quad & 0.062722eV \\ (U_2 - E_0)_2 = \quad & (U_2 - E_0)_0\left(\arctan\sqrt{\frac{U_2-U_{00}}{(U_2-E_0)_1}-1}+\arctan\sqrt{\frac{E_0-U_4}{(U_2-E_0)_1}}\right)^2 \\ = \quad & 0.0084386eV\left(\arctan\sqrt{\frac{1.636}{0.062722}-1}+\arctan\sqrt{\frac{0.066}{0.062722}}\right)^2 \\ = \quad & 0.039804eV \\ (U_2 - E_0)_3 = \quad & 0.045603eV \\ (U_2 - E_0)_4 = \quad & 0.043881eV \\ (U_2 - E_0)_5 = \quad & 0.044370eV \\ (U_2 - E_0)_6 = \quad & 0.044229eV \\ (U_2 - E_0)_7 = \quad & 0.044269eV, \\ \downarrow & \\ U_2 - E_0 = \quad & 0.044eV \end{aligned} \tag{A.21}$$

With (A.17), we obtain the quantum dot ground state energy as

$$E_0 = U_2 - (U_2 - E_0) = -0.084 - 0.044 = -0.128eV, \tag{A.22}$$

and the effective height of the internal barrier as

$$E_0 - U_{00} = -0.128 + 1.720 = 1.592eV. \tag{A.23}$$

At the same time, from ((1176)) we obtain the p-region potential

$$U_v = E_0 - \left(\frac{1}{2} + \frac{M_n}{M_p}\right)T = -0.128 - \left(\frac{1}{2} + \frac{0.065}{0.5}\right)0.026 = -0.144eV, \tag{A.24}$$

We also obtain the potential of the lower level separation barrier (A.18),

$$U_4 = U_v - 0.05 = -0.144 - 0.05 = -0.194eV, \tag{A.25}$$

and the height of this barrier

$$U_2 - U_4 = -0.084 + 0.194 = 0.110eV. \tag{A.26}$$

From (A.24) and (A.1), we obtain the effective resonance energy (A.5),

$$\hbar\bar{\omega}_0 = U_c - U_v = 0.068 + 0.144 = 0.212eV. \tag{A.27}$$

The potential U_v of the p-region is given by an acceptor concentration N_A from (3.466) with (3.149),

$$N_A = N_v e^{U_v/T} = 8.9\times10^{18}e^{-0.144/0.026} = 3.5\times10^{16}cm^{-3}. \tag{A.28}$$

With the expressions (3.343), (3.346), (3.344), (3.345), (3.347), and (3.348), with (A.12), (A.21), (A.10), (A.11), (A.23) and (A.19), for the two quantum dot wave functions we obtain the wave numbers,

$$k_1 = \frac{1}{\hbar c}\sqrt{2M_n c^2(E_1 - U_1)} \tag{A.29}$$

$$= \frac{1}{197eVnm}\sqrt{2\times0.065\times0.511\times10^6eV0.027eV}$$

$$= 0.21498nm^{-1},$$

$$k_0 = \frac{1}{\hbar c}\sqrt{2M_p c^2(U_2 - E_0)} \tag{A.30}$$

$$= \frac{1}{197eVnm}\sqrt{2\times0.5\times0.511\times10^6eV0.044eV}$$

$$= 0.76115nm^{-1},$$

and the attenuation coefficients of in the potential barriers,

$$\alpha_1 = \frac{1}{\hbar c}\sqrt{2M_n c^2(U_0 - E_1)} \tag{A.31}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.065\times 0.511\times 10^6 eV 0.145eV}$$

$$= 0.49820nm^{-1}$$

$$\alpha_3 = \frac{1}{\hbar c}\sqrt{2M_n c^2(U_3 - E_1)} \tag{A.32}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.065\times 0.511\times 10^6 eV 0.063eV}$$

$$= 0.32839nm^{-1}$$

$$\alpha_0 = \frac{1}{\hbar c}\sqrt{2M_p c^2(E_0 - U_{00})} \tag{A.33}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.5\times 0.511\times 10^6 eV 1.592eV}$$

$$= 4.5784nm^{-1}$$

$$\alpha_4 = \frac{1}{\hbar c}\sqrt{2M_p c^2(E_0 - U_4)} \tag{A.34}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.5\times 0.511\times 10^6 eV 0.066eV}$$

$$= 0.93222nm^{-1}.$$

From (3.351) and (3.367), we obtain the phase constants of the two quantum dot wave functions,

$$\varphi_1 = -\arctan\frac{\alpha_1}{k_1} = -\arctan\left(\frac{0.49820}{0.21498}\right) = -1.1634rad \tag{A.35}$$

$$\varphi_0 = -\arctan\frac{\alpha_0}{k_0} = -\arctan\left(\frac{4.5784}{0.76115}\right) = -1.4061rad, \tag{A.36}$$

while from (3.362) with (A.10) and (A.11), and from (3.376) with (A.23) and (A.19), we obtain the amplitudes of these wave functions,

$$A_1 = \sqrt{2}\left(x_0 - x_1 + \frac{\hbar c}{\sqrt{2M_n c^2(U_0 - E_1)}} + \frac{\hbar c}{\sqrt{2M_n c^2(U_3 - E_1)}}\right)^{-\frac{1}{2}} \tag{A.37}$$

$$= \sqrt{2}\left(10nm + \frac{197eVnm}{\sqrt{2\times 0.065\times 0.511\times 10^6 eV 0.145eV}}\right.$$

$$\left. + \frac{197eVnm}{\sqrt{2\times 0.065\times 0.511\times 10^6 eV 0.063eV}}\right)^{-\frac{1}{2}} = 0.36451nm^{-\frac{1}{2}}$$

$$A_0 = \sqrt{2}\left(x_4 - x_2 + \frac{\hbar c}{\sqrt{2M_p c^2(E_0 - U_{00})}} + \frac{\hbar}{\sqrt{2M_p c^2(E_0 - U_4)}}\right)^{-\frac{1}{2}} \tag{A.38}$$

$$= \sqrt{2}\left(3nm + \frac{197eVnm}{\sqrt{2\times 0.5\times 0.511\times 10^6 eV 1.592eV}} + \frac{197eVnm}{\sqrt{2\times 0.5\times 0.511\times 10^6 eV 0.066eV}}\right)^{-\frac{1}{2}}$$

$$= 0.68270nm^{-\frac{1}{2}}.$$

With these coefficients, we obtain the higher level wave function (3.361),

$$\psi_1(x) = \begin{cases} A_1\sqrt{\frac{E_1-U_1}{U_3-U_1}}e^{-\alpha_3(x_1-x)}, & x_0 - 20 \le x \le x_0 - 10 \\ = 0.36451\sqrt{\frac{0.027}{0.090}}e^{-0.32839(x_0-10-x)} & \\ = 0.19965e^{-0.32839(x_0-10-x)} & \\ A_1\cos[k_1(x_0 - x) + \varphi_1], & x_0 - 10 \le x \le x_0 \\ = 0.36451\cos[0.21498(x_0 - x) - 1.1634] & \\ A_1\sqrt{\frac{E_1-U_1}{U_0-U_1}}e^{-\alpha_1(x-x_0)}, & x_0 \le x \le x_2, \\ = 0.36451\sqrt{\frac{0.027}{0.172}}e^{-0.49820(x-x_0)} & \\ = 0.14442e^{-0.49820(x-x_0)} & \end{cases} \tag{A.39}$$

and the lower level wave function (3.375),

$$\psi_0(x) = \begin{cases} A_0\sqrt{\frac{U_2-E_0}{U_2-U_{00}}}e^{-\alpha_0(x_2-x)}, & x_0 \le x \le x_2 \\ = 0.68270\sqrt{\frac{0.044}{1.636}}e^{-4.5784(x_2-x)} & \\ = 0.11196e^{-4.5784(x_2-x)} & \\ A_0\cos[k_0(x - x_2) + \varphi_0], & x_2 \le x \le x_2 + 3 \\ = 0.68270\cos[0.76115(x - x_2) - 1.4061] & \\ A_0\sqrt{\frac{U_2-E_0}{U_2-U_4}}e^{-\alpha_4(x-x_4)}, & x_2 + 3 \le x \le x_2 + 6, \\ = 0.68270\sqrt{\frac{0.044}{0.110}}e^{-0.93222(x-x_2-3)} & \\ = 0.43178e^{-0.93222(x-x_2-3)} & \end{cases} \tag{A.40}$$

We distinguish the continuity coordinate values, for the higher level wave function,

$$\psi_1(x_0 - 10) = 0.36451\sqrt{\frac{0.027}{0.090}} = 0.36451\cos(0.21498\times 10 - 1.1634) \quad \text{(A.41)}$$

$$= 0.20nm^{-\frac{1}{2}}$$

$$\psi_1(x_0) = 0.36451\sqrt{\frac{0.027}{0.172}} = 0.36451\cos(-1.1634) \quad \text{(A.42)}$$

$$= 0.1444nm^{-\frac{1}{2}}$$

and for the lower level wave function,

$$\psi_0(x_2) = 0.68270\sqrt{\frac{0.044}{1.636}} = 0.68270\cos(-1.4061) \quad \text{(A.43)}$$

$$= 0.1119nm^{-\frac{1}{2}}$$

$$\psi_0(x_2 + 3) = 0.68270\sqrt{\frac{0.044}{0.110}} = 0.68270\cos(0.76115\times 3 - 1.4061) \quad \text{(A.44)}$$

$$= 0.43nm^{-\frac{1}{2}}$$

For simplicity, we considered the energy values with a precision of only $1mV$, and the distances with a precision of $0.1nm$. As a result, these wave functions are approximated with a precision of 3 significant figures around the limits x_0 and x_2 of the internal barrier, and a lower precision of only 2 significant figures around the limits of the separation barriers. This precision is sufficient for the evaluation of the overlap function and dipole moment in the separation barrier. From (4.155), we obtain the approximate value

$$\begin{aligned} x_2 - x_0 &\approx \frac{\eta^2\varepsilon_0(U_c - U_v)}{e^2N_e} - \frac{x_0 - x_1}{2} - \frac{x_4 - x_2}{2} \\ &= 61.528 - 5.000 - 1.500 = 55.0nm. \end{aligned} \quad \text{(A.45)}$$

For a narrower higher level potential well, $x_0 - x_1 = 3.5nm$, the sequence (A.12) for the ground state energy of this well becomes

$$
\begin{aligned}
(E_1-U_1)_0 = \quad & \frac{\hbar^2c^2}{2M_nc^2(x_0-x_1)^2} = \frac{197^2eV^2nm^2}{2\times0.065\times0.511\times10^6eV3.5^2nm^2} \\
= \quad & 0.047691eV \\
(E_1-U_1)_1 = \quad & (E_1-U_1)_0\left(\arctan\sqrt{\frac{U_0-E_1}{(E_1-U_1)_0}}+\arctan\sqrt{\frac{U_3-E_1}{(E_1-U_1)_0}}\right)^2 \\
= \quad & 0.047691eV\left(\arctan\sqrt{\frac{0.145}{0.047691}}+\arctan\sqrt{\frac{0.063}{0.047691}}\right)^2 \\
= \quad & 0.17305eV \\
(E_1-U_1)_2 = \quad & (E_1-U_1)_0\left(\arctan\sqrt{\frac{U_0-E_1}{(E_1-U_1)_1}}+\arctan\sqrt{\frac{U_3-E_1}{(E_1-U_1)_1}}\right)^2 \\
= \quad & 0.047691eV\left(\arctan\sqrt{\frac{0.145}{0.17305}}+\arctan\sqrt{\frac{0.063}{0.17305}}\right)^2 \\
= \quad & 0.078643eV \\
(E_1-U_1)_3 = \quad & 0.13238eV \\
(E_1-U_1)_4 = \quad & 0.95089eV \\
(E_1-U_1)_5 = \quad & 0.11805eV,
\end{aligned}
$$

which is

$$E_1-U_1 = 0.109eV. \tag{A.46}$$

We obtain the potential of the higher level well,

$$U_1 = E_1-(E_1-U_1) = 0.055-0.109 = -0.054eV, \tag{A.47}$$

with the barriers

$$U_0-U_1 = 0.200+0.054 = 0.254eV \tag{A.48}$$

$$U_3-U_1 = 0.118+0.054 = 0.172eV \tag{A.49}$$

and the quantum dot density creating this well,

$$
\begin{aligned}
N_e = \quad & \frac{M_nc^2T}{\pi\hbar^2c^2}\ln\left(1+e^{-\frac{U_1}{T}}\right) \\
= \quad & \frac{0.065\times0.511\times10^60.026}{\pi197^2nm^2}\ln\left[1+\exp\left(\frac{0.054}{0.026}\right)\right] \\
= \quad & 1.5547\times10^{-2}nm^{-2} = 1.5547\times10^{16}m^{-2}.
\end{aligned} \tag{A.50}
$$

With this quantum dot density, from (3.471) we obtain the potential of the lower level well,

$$\begin{aligned} U_2 = \quad & T\ln\left[\exp\left(\frac{\pi\hbar^2c^2N_e}{M_pc^2T}\right)-1\right] \\ = \quad & 0.026eV\ln\left[\exp\left(\frac{\pi 197^2 1.5547\times10^{-2}}{0.5\times0.511\times10^6 0.026}\right)-1\right] \\ = \quad & -0.028808eeV \approx -0.029eV. \end{aligned} \tag{A.51}$$

with a height of the internal barrier

$$U_2 - U_{00} = -0.029 + 1.720 = 1.691eV. \tag{A.52}$$

We consider a potential of the separation barrier (A.18),

$$U_4 = U_v - 0.05eV, \tag{A.53}$$

and an effective height of this barrier (A.19),

$$E_0 - U_4 = 0.066eV. \tag{A.54}$$

We select the width $x_4 - x_2 = 2nm$ of the lower level potential well, and calculate the ground state energy of this well

$$\begin{aligned} (U_2-E_0)_0 = \quad & \frac{\hbar^2c^2}{2M_pc^2(x_4-x_2)^2} = \frac{197^2eV^2nm^2}{2\times0.5\times0.511\times10^6eV2^2nm^2} \\ = \quad & 0.018987eV \\ (U_2-E_0)_1 = \quad & (U_2-E_0)_0\left(\arctan\sqrt{\frac{U_2-U_{00}}{(U_2-E_0)_0}-1}+\arctan\sqrt{\frac{E_0-U_4}{(U_2-E_0)_0}}\right)^2 \\ = \quad & 0.018987eV\left(\arctan\sqrt{\frac{1.691}{0.018987}-1}+\arctan\sqrt{\frac{0.066}{0.018987}}\right)^2 \\ = \quad & 0.15611eV \\ (U_2-E_0)_2 = \quad & (U_2-E_0)_0\left(\arctan\sqrt{\frac{U_2-U_{00}}{(U_2-E_0)_1}-1}+\arctan\sqrt{\frac{E_0-U_4}{(U_2-E_0)_1}}\right)^2 \\ = \quad & 0.018987eV\left(\arctan\sqrt{\frac{1.691}{0.12278}-1}+\arctan\sqrt{\frac{0.066}{0.12278}}\right)^2 \\ = \quad & 0.10757eV \\ (U_2-E_0)_3 = \quad & 0.11895eV \\ (U_2-E_0)_4 = \quad & 0.11600eV \\ (U_2-E_0)_5 = \quad & 0.11674eV \\ (U_2-E_0)_6 = \quad & 0.11655eV \\ (U_2-E_0)_7 = \quad & 0.11660eV, \end{aligned} \tag{A.55}$$

which is

$$U_2 - E_0 = 0.117eV. \tag{A.56}$$

With this value and (A.51), we obtain the quantum dot ground state energy

$$E_0 = U_2 - (U_2 - E_0) = -0.029 - 0.117 = -0.146eV, \tag{A.57}$$

and the effective height of the internal barrier,

$$E_0 - U_{00} = -0.146 + 1.720 = 1.574eV. \tag{A.58}$$

From (A.4), we obtain the p-region potential

$$\begin{aligned} U_v = E_0 - \left(\tfrac{1}{2} + \tfrac{M_n}{M_p}\right)T = \quad & -0.146 - \left(\tfrac{1}{2} + \tfrac{0.065}{0.5}\right)0.026 = -0.16238eV \\ \approx \quad & -0.162eV \end{aligned} \tag{A.59}$$

With this potential, we obtain the potential of the separation barrier of the quantum dot lower level well (A.53),

$$U_4 = U_v - 0.05 = -0.162 - 0.05 = -0.212eV \tag{A.60}$$

and the height of this barrier,

$$U_2 - U_4 = -0.029 + 0.212 = 0.183eV. \tag{A.61}$$

From (A.1) and (A.59), , we obtain the effective resonance energy (A.5),

$$\hbar\bar{\omega}_0 = U_c - U_v = 0.068 + 0.162 = 0.230eV. \tag{A.62}$$

From (3.466), we obtain the acceptor concentration N_A, with the potential U_v of the p conduction region,

$$N_A = N_v e^{U_v/T} = 8.9\times10^{18} e^{-0.162/0.026} = 1.7515\times10^{16} cm^{-3}. \tag{A.63}$$

With the expressions (3.343), (3.346), (3.344), (3.345), (3.347), and (3.348), with (A.46), (A.56), (A.10), (A.11), (A.58) and (A.54), for the two quantum dot wave functions we obtain the wave numbers,

$$\begin{aligned} k_1 &= \tfrac{1}{\hbar c}\sqrt{2M_n c^2(E_1 - U_1)} \\ &= \frac{1}{197eVnm}\sqrt{2\times0.065\times0.511\times10^6 eV 0.109eV} \\ &= 0.43195nm^{-1}, \end{aligned} \tag{A.64}$$

$$\begin{aligned} k_0 &= \tfrac{1}{\hbar c}\sqrt{2M_p c^2(U_2 - E_0)} \\ &= \frac{1}{197eVnm}\sqrt{2\times0.5\times0.511\times10^6 eV 0.117eV} \\ &= 1.2412nm^{-1}, \end{aligned} \tag{A.65}$$

and the attenuation coefficients of in the potential barriers,

$$\alpha_1 = \frac{1}{\hbar c}\sqrt{2M_n c^2(U_0 - E_1)} \tag{A.66}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.065\times 0.511\times 10^6 eV 0.145eV}$$

$$= 0.49820nm^{-1}$$

$$\alpha_3 = \frac{1}{\hbar c}\sqrt{2M_n c^2(U_3 - E_1)} \tag{A.67}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.065\times 0.511\times 10^6 eV 0.063eV}$$

$$= 0.32839nm^{-1}$$

$$\alpha_0 = \frac{1}{\hbar c}\sqrt{2M_p c^2(E_0 - U_{00})} \tag{A.68}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.5\times 0.511\times 10^6 eV 1.574eV}$$

$$= 4.5525nm^{-1}$$

$$\alpha_4 = \frac{1}{\hbar c}\sqrt{2M_p c^2(E_0 - U_4)} \tag{A.69}$$

$$= \frac{1}{197eVnm}\sqrt{2\times 0.5\times 0.511\times 10^6 eV 0.066eV}$$

$$= 0.93222nm^{-1}.$$

From (3.351) and (3.367), we obtain the phase constants of the two quantum dot wave functions,

$$\varphi_1 = -\arctan\frac{\alpha_1}{k_1} = -\arctan\left(\frac{0.49820}{0.43195}\right) = -0.85650rad \tag{A.70}$$

$$\varphi_0 = -\arctan\frac{\alpha_0}{k_0} = -\arctan\left(\frac{4.5525}{1.2412}\right) = -1.3046rad, \tag{A.71}$$

while from (3.362) with (A.10) and (A.11), and from (3.376) with (A.58) and (A.54), we obtain the amplitudes of these wave functions,

$$A_1 = \sqrt{2}\left(x_0 - x_1 + \frac{1}{\alpha_1} + \frac{1}{\alpha_3}\right)^{-\frac{1}{2}} \tag{A.72}$$

$$= \sqrt{2}\left(3.5nm + \frac{1}{0.4982nm^{-1}} + \frac{1}{0.32839nm^{-1}}\right)^{-\frac{1}{2}} = 0.48358nm^{-\frac{1}{2}}$$

$$A_0 = \sqrt{2}\left(x_4 - x_2 + \frac{1}{\alpha_0} + \frac{1}{\alpha_4}\right)^{-\frac{1}{2}} \tag{A.73}$$

$$= \sqrt{2}\left(2nm + \frac{1}{4.5525nm^{-1}} + \frac{1}{0.93222nm^{-1}}\right)^{-\frac{1}{2}} = 0.77940nm^{-\frac{1}{2}}$$

From (4.155),

$$\begin{aligned} x_2 - x_0 = \; & \frac{\eta^2\varepsilon_0(U_c - U_v)}{e^2 N_e} \\ & - \frac{A_1^2}{2}\left[\frac{1}{2}(x_0 - x_1)^2 + \frac{x_0 - x_1}{\alpha_3} - \frac{1}{2\alpha_1^2}\frac{E_1 - U_1}{U_0 - U_1} + \frac{1}{2\alpha_3^2}\frac{E_1 - U_1}{U_3 - U_1}\right. \\ & \left. + \frac{1}{4k_1^2}\left(\frac{U_0 - E_1 - (E_1 - U_1)}{U_0 - U_1} - \frac{U_3 - E_1 - (E_1 - U_1)}{U_3 - U_1}\right)\right] \\ & - \frac{A_0^2}{2}\left[\frac{1}{2}(x_4 - x_2)^2 + \frac{x_4 - x_2}{\alpha_4} - \frac{1}{2\alpha_0^2}\frac{U_2 - E_0}{U_2 - U_{00}} + \frac{1}{2\alpha_4^2}\frac{U_2 - E_0}{U_2 - U_4}\right. \\ & \left. + \frac{1}{4k_0^2}\left(\frac{E_0 - U_{00} - (U_2 - E_0)}{U_2 - U_{00}} - \frac{E_0 - U_4 - (U_2 - E_0)}{U_2 - U_4}\right)\right], \end{aligned} \tag{A.74}$$

we obtain

$$\begin{aligned} x_2 - x_0 = \; & \frac{3.3^2 8.854\times10^{-12}CV^{-1}m^{-1}0.230V10^{-9}mnm^{-1}}{1.6\times10^{-19}C1.5547\times10^{-2}nm^{-2}} \\ & - \frac{0.48358^2}{2}\left[\frac{3.5^2}{2} + \frac{3.5}{0.32839} - \frac{1}{2\times0.5^2}\frac{0.109}{0.254} + \frac{1}{2\times0.33^2}\frac{0.109}{0.172}\right. \\ & \left. + \frac{1}{4\times0.431^2}\left(\frac{0.145 - 0.109}{0.254} - \frac{0.063 - 0.109}{0.172}\right)\right] \\ & - \frac{0.77963^2}{2}\left[\frac{2^2}{2} + \frac{2}{0.93222} - \frac{1}{2\times4.6^2}\frac{0.117}{1.691} + \frac{1}{2\times0.93^2}\frac{0.117}{0.183}\right. \\ & \left. + \frac{1}{4\times1.241^2}\left(\frac{1.574 - 0.117}{1.691} - \frac{0.066 - 0.117}{0.183}\right)\right] \\ = \; & 8.9151 - 2.2346 - 1.4267 = 5.2218nm \\ \approx \; & \frac{\eta^2\varepsilon_0(U_c - U_v)}{e^2 N_e} - \frac{x_0 - x_1}{2} - \frac{x_4 - x_2}{2} \\ \sim \; & 8.9151 - 1.75 - 1.000 = 6.1651nm. \end{aligned} \tag{A.75}$$

Appendix B

Particle in a System of Oscillators

We consider a particle with a mass M, in a system of N harmonic oscillators of mass $\mathcal{M}$ in the potential wells $U_n(\vec{r}_n)$, under the action of a time dependent potential $V(\vec{r},t)$. With the interaction potential $\sum_{n=1}^{N} V_n(\vec{r}-\vec{r}_n)$ of this particle with the oscillators, the Lagrangian of the total system is a follows

$$L\left(\vec{r},\vec{r}_n,\dot{\vec{r}},\dot{\vec{r}}_n,t\right)=\frac{M}{2}\dot{\vec{r}}^2+\frac{\mathcal{M}}{2}\sum_{n=1}^{N}\dot{\vec{r}}_n^2-V(\vec{r},t)$$

$$-\sum_{n=1}^{N} V_n(\vec{r}-\vec{r}_n)-\sum_{n=1}^{N} U_{\mathrm{n}}(\vec{r}_n). \tag{B.1}$$

We obtain the Lagrange equations as:

$$M\ddot{\vec{r}}=-\frac{\partial}{\partial\vec{r}}V(\vec{r},t)-\sum_{n=1}^{n}\frac{\partial}{\partial\vec{r}}V_n(\vec{r}-\vec{r}_n) \tag{B.2}$$

$$\mathcal{M}\ddot{\vec{r}}_n=-\frac{\partial}{\partial\vec{r}_n}V_n(\vec{r}-\vec{r}_n)-\frac{\partial}{\partial\vec{r}_n}U_n(\vec{r}_n)=\frac{\partial}{\partial\vec{r}}V_n(\vec{r}-\vec{r}_n)-\frac{\partial}{\partial\vec{r}_n}U_n(\vec{r}_n). \tag{B.3}$$

We also obtain an equation of motion for this particle with the coupled oscillator system under the action of the potential $V(\vec{r},t)$,

$$M\ddot{\vec{r}}+\sum_{n=1}^{n}\left[\mathcal{M}\ddot{\vec{r}}_n+\frac{\partial}{\partial\vec{r}_n}U_n(\vec{r}_n)\right]=-\frac{\partial}{\partial\vec{r}}V(\vec{r},t). \tag{B.4}$$

It is interesting that we can reduce this equation for the total system, particle + system of oscillators, to a dynamic equation only for the particle, by using a simpler Lagrangian, with the kinetic energies induced by the two potentials of interaction, $V(\vec{r},t)$ and $\sum_{n=1}^{N} V_n(\vec{r}-\vec{r}_n)$,

$$L(\vec{r},\dot{\vec{r}},t)=\frac{M}{2}\dot{\vec{r}}+\frac{\mathcal{M}}{2}\sum_{n=1}^{N}(\dot{\vec{r}}-\dot{\vec{r}}_n)^2-V(\vec{r},t)-\sum_{n=1}^{N} V_n(\vec{r}-\vec{r}_n). \tag{B.5}$$

In this case, the Lagrange equation,

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial}{\partial\dot{\vec{r}}}L(\vec{r},\dot{\vec{r}},t)=\frac{\partial}{\partial\vec{r}}L(\vec{r},\dot{\vec{r}},t), \tag{B.6}$$

is

$$(M+N\mathcal{M})\ddot{\vec{r}}-\mathcal{M}\sum_{n=1}^{N}\ddot{\vec{r}}_n=-\frac{\partial}{\partial\vec{r}}V(\vec{r},t)-\sum_{n=1}^{N}\frac{\partial}{\partial\vec{r}}V_n(\vec{r}-\vec{r}_n). \tag{B.7}$$

With a symmetry condition of the oscillator distribution around the particle,

$$\mathcal{M}\sum_{n=1}^{N}\ddot{\vec{r}}_n=0 \tag{B.8}$$

$$\sum_{n=1}^{N} \frac{\partial}{\partial \vec{r}} V_n(\vec{r} - \vec{r}_n) = 0, \tag{B.9}$$

for this particle we obtain an equation of motion

$$(M + N\mathcal{M})\ddot{\vec{r}} = -\frac{\partial}{\partial \vec{r}} V(\vec{r}, t), \tag{B.10}$$

with an effective mass

$$\overline{M} = M + N\mathcal{M}. \tag{B.11}$$

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SUBJECT INDEX

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Eliade Stefanescu graduated the Faculty of Electronics, Section of Physicist Engineers, in 1970, and obtained a PhD in Theoretical Physics in 1990. As a Scientist in 1976 and a Senior Scientist III in 1978, he worked for the development of the technology of semiconductor devices. In 1978, he worked on optoelectronic devices. From 1987 to 1990 as a Senior Scientist II, he worked in the field of open quantum physics. In 1991, he discovered that the penetrability of a potential barrier can be increased by coupling to a dissipative system, and described the decay spectrum of some cold fission modes. As a Senior Scientist I, in 1997 he developed a microscopic theory of open quantum systems, and in 2007 discovered a physical principle for the heat conversion into usable energy. In 2014, he produced a unitary relativistic quantum theory. In the years 1995-2000, he held a course called Dissipative Systems for the master degree. He is a member of the American Chemical Society and the Academy of Romanian Scientists.