Journal of Modern Physics, 2024, 15, 1615-1620
https://www.scirp.org/journal/jmp
ISSN Online: 2153-120X
ISSN Print: 2153-1196

Effective Qubit Emerging from the Nanoheterointerface Two-Dimensional Electron Gas Photodynamics

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How to cite this paper: Anagnostakis, E.A. (2024) Effective Qubit Emerging from the Nanoheterointerface Two-Dimensional Electron Gas Photodynamics. *Journal of Modern Physics*, **15**, 1615-1620.
https://doi.org/10.4236/jmp.2024.1511069

Received: August 28, 2024
Accepted: September 27, 2024
Published: September 30, 2024

Abstract

An "Eigenstate Adjustment Autonomy" Model, permeated by the Nanosystem's Fermi Level Pinning along with its rigid Conduction Band Discontinuity, compatible with pertinent Experimental Measurements, is being employed for studying how the Functional Eigenstate of the Two-Dimensional Electron Gas (2DEG) dwelling within the Quantum Well of a typical Semiconductor Nanoheterointerface evolves versus (cryptographically) selectable consecutive Cumulative Photon Dose values. Thus, it is ultimately discussed that the experimentally observed (after a Critical Cumulative Photon Dose) Phenomenon of 2DEG Negative Differential Mobility allows for the Nanosystem to exhibit an Effective Qubit Specific Functionality potentially conducive to (Telecommunication) Quantum Information Registering.

Keywords

Semiconductor Nanoheterointerface, Two-Dimensional Electron Gas, Nanosystem Photodynamics, Sign Qubit, Quantum Information Registering

1. Introduction

The Functional Behaviour of a typical Semiconductor Nanoheterointerface Quantum Well 2DEG (e.g. Figs. 2 & 3 of Ref. [1] and Fig. 3 of Ref. [2]) is primarily representable by the Two-Dimensional Electrons Areal Density (2DEG Sheet Concentration), ζ, and the respective Mobility, μ, on the one hand [1] [3], and by the Schrödinger Eigenstates [2] [4] pertaining to the Fermionic Quantum Causality [5] of such a Particle Ensemble. The performance of the 2DEG is parametrically controlled by the features of the above Quantum Well hosting its oscillatory dwelling and by the (Persistent-Photoconductivity-Supportive) Low Absolute Temperature of the employed overall Nanodevice, and is driven by the influence of the External (Optical/Photonic or/and Nanoheterointerface-Biasing dc Voltage) Signal. Additionally, the Phenomenon of Negative Differential Mobility ($d\mu/d\delta < 0|\delta > \Delta$) of such a 2DEG can become experimentally manifested, if the Nanosystem has been exposed to a Cumulative Photon Dose, δ, higher than a case-wise specific Critical one, Δ [1] [3].

Within the extension of a typical Semiconductor Nanoheterointerface (NHI), the Energy Band Bending of the Quantum Barrier Side and the Conductive Channel is determined [2] [4] by the Density of the neighbouring Ionised Impurity Charge and by the Total Electric Field, any Effective Non-Built-In Electric Field being included. Thus, on the one hand, the Bottoms of the 2DEG Subbands are Quantum Mechanically Computable, and, on the other hand, by virtue of the Thermodynamic Equilibrium Condition, the realistic Sheet Concentration of the NHI Quantum Well 2DEG is linked to an ultimately Homogeneous Fermi Level spanning the entire Nanoheterodiode.

At each Instance of such a Dynamic Equilibrium, the Energy Top of the actually Occupied NHI 2DEG States gets aligned to the respectively valid Fermi Level,

$$\varepsilon + \frac{\zeta}{\rho} = F, \tag{1}$$

where F is the Fermi Level, ε is the Energy Bottom of the Fundamental 2DEG Subband (considered to be the sole initially occupied Subband, the Electric Quantum Limit being approached by a conventional NHI primarily functioning at Ambient Temperatures lying in the Region of Absolute Zero), ζ is the Instantaneous 2DEG Sheet Concentration valid within the NHI Quantum Well, and ρ is the (Parabolic-Approximation) Theoretical Two-Dimensional Density of States (Number of States per Unit Lateral Area and per Unit Energy Increment) allowed for Conduction-Band Electrons having the NHI-Growth-Axis Component of the de Broglie Wavevector quantised.

By common practice, the Method of Modulation Doping embeds an intensely dense Donor Spatial Distribution in the Wider-Bandgap Subregion of the NHI of a typical Epitaxially Grown Semiconductor Diodic Nanoheterodevice. Given that the representative Energy Level of these Donors, D, becomes adequately Deep (in the framework of the Nanostructure Energy Gap Spatial Distribution), it is acceptably expected (and experimentally indirectly verifiable) that the Nanodevice Fermi Level, F, gets “pinned” in the Energy Locus D and remains there (exhibiting a Negligible Effective Rate of Change), whilst the entailed NHI functions owing to selected experimental procedure in the Vicinity of the above Quantum Limit [2] [4].

2. Eigenstate Adjustment Autonomy Model

The Dynamics of the Loci of the Energy Levels is now taken into account versus Regulated Consecutive Photon-Doses being absorbed by the traced Semiconductor Nanoheterodevice (having the outer surface of its Wider-Bandgap Epitaxial Layer exposed to the Photon Flows), it is acceptably provable [2] [4] that:

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}\delta} = -\frac{1}{\rho} \cdot \frac{\mathrm{d}\zeta}{\mathrm{d}\delta}: \tag{2}$$

This Relation provides the Cumulative-Photon-Dose (δ) Rate of Evolution of the Energy Level ε of the Fundamental 2DEG-Eigenstate on the basis of the Experimentally Discernible versus δ Rate of Enhancement of the Areal Density ζ of the 2DEG localised within the Quantum Well of the probed NHI. Through this viewpoint, the Relation describes the Photodynamics of the evolving Modification of the Fundamental Eigenstate of the NHI during the Procedure of successive appropriate Photon-Dose Transmissions being consecutively received by the Nanoheterodevice: To each Experimentally Obtainable Photoenhancement $\Delta\zeta(\delta)$ of the 2DEG Sheet Concentration ζ (considered with respect to the Dark Value of ζ and consequent upon a certain Instantaneous Total Photon-Dose δ) there corresponds a Red Photoshift $\Delta\varepsilon(\delta)$ of the Energy Locus ε of the 2DEG Fundamental Eigenstate (considered with respect to the Dark Value of ε), expectedly (through integrating versus δ) expressible as:

$$\Delta\varepsilon(\delta) = -\frac{1}{\rho} \cdot \Delta\zeta(\delta). \tag{3}$$

In Article [4], a Finite-Differences Algorithm is produced and utilised for the Recurrent Arithmetic Solution of the Schrödinger Equation concerning the Stationary de Broglie Wavefunction of a representative Two-Dimensional Conduction-Band Electron confined within the Quantum Well of the typical NHI: For the each-time Absorbed Cumulative Photon-Dose δ and respective Experimental Sheet-Concentration Photoenhancement $\Delta\zeta(\delta)$, the Algorithm converges to an Optimal Spatial Width of a Simulative Rectangular Quantum Well compatible with the Fundamental-Eigenenergy Red Photoshift $\Delta\varepsilon(\delta)$. For each δ, the Algorithm optimises the respective Simulative-Well Width (which gets expanding versus δ at instantaneous Rate induced by the each-time externally regulated δ) under the Physical Condition of the Energy Depth of the Well always remaining equal to the Conduction-Band Discontinuity dictated by the two Different-Semiconductor Epitaxial Layers participating in the studied NHI. As regards the 2DEG (First) Excited Eigenstate Energy Level, it also expectedly exhibits gradual Red Photoshift (versus intaken Instantaneous Total Photon-Dose δ), owing to which it evolves sinking towards the Pinned Fermi Level: At the exact Instance of Saturation of the Capacity Z (Maximum Two-Dimensional-Electron Sheet Concentration) of the 2DEG Fundamental Subband this Excited-Eigenenergy Level arrives momentarily at the Energy Locus of the Pinned Fermi Level of the entailed Nanodevice. Then,

$$\zeta = Z \,\&\, \frac{\zeta}{\rho} = \frac{Z}{\rho}, \tag{4}$$

the respective Instantaneous realistic Separation valid between the Energy Loci of the Fundamental and the (First) Excited 2DEG Eigenstates being unveiled. It is at this exact Instance that the experimentally monitored 2DEG Differential Mobility momentarily vanishes, just before the appearance of the Negative Differential Mobility Regime of the Photodynamic Evolution of the probed Nanosystem.

The Nanosystem's Fermi Level Pinning along with its rigid Nanoheterointerfacial Conduction Band Discontinuity taken advantage of in the above Algorithm, both being Endosystemic Features [2] [4], constitute the Character essence of what we conceive as the Eigenstate Adjustment Autonomy Model (the "EAA Model") discussed herewith.

We have recently enriched the above Algorithm so that for each Instantaneous Total Photon-Dose Intaken by the gradually Photomodified Nanosystem it can also be tracing the connected Energy Locus of the Excited 2DEG Eigenstate, the respective Effective Excited Wavefunction, and the evolving Photoshrinking of the NHI-Quantum-Barrier Penetration Length both of the Fundamental and the Excited 2DEG Wavefunction. We are also currently exploiting these Penetration Lengths as a kind of "Feedback Criterion" for accentuating the Mobility-wise Self-Consistency of the EAA Model.

3. Emerging Effective Qubit

Inspired by that the experimentally monitored 2DEG Differential Mobility ($\mathrm{d}\mu/\mathrm{d}\delta$) Sign Flipping (from + to −) is attributable to the heralding of ignition of Electron-Occupation of the Excited Energy-Subband of the Semiconductor NHI Quantum Well, we come to consider [6] that this Differential Mobility Sign (DMS) exhibits a Qubit Functionality: If, on the one hand, the Fundamental Quantum Eigenstate of the 2DEG serves as the Actually Important one, the DMS is found to be Positive. If, on the other hand, the Excited Quantum Eigenstate of the 2DEG serves (by virtue of a Cumulative Photon Dose exceeding the Critical Value marking the Nanosystem-Switching "Temporal Interface") as the Actually Important one, the DMS is found to be Negative.

Equivalently, against the Orthocanonical Base $\{|-\rangle,|+\rangle\}$, where representatively permissibly:

$$|-\rangle=[0\ 1]^{\mathrm{T}}\ \&\ |+\rangle=[1\ 0]^{\mathrm{T}}, \tag{5}$$

the Dirac General State Vector of the DMS treated as a Qubit ("DMS Qubit") is expected to be expressible through the Superposition:

$$|\Sigma\rangle=\alpha|-\rangle+\theta|+\rangle, \tag{6}$$

under the Normalisation Condition:

$$|\alpha|^2+|\theta|^2=1. \tag{7}$$

Additionally, given that:

$$\boldsymbol{\sigma}|-\rangle=|+\rangle\ \&\ \boldsymbol{\sigma}|+\rangle=|-\rangle \tag{8}$$

(with $\boldsymbol{\sigma}$ being the First of the Triad of Pauli Matrices), the DMS Flipping can be encoded through the Operator $\boldsymbol{\sigma}$ acting on the DMS Ket Representation.

Furthermore, given as well that, when acting upon the Superpositional State Vector:

$$|s\rangle = \frac{1}{\sqrt{2}}\left(|-\rangle + |+\rangle\right), \tag{9}$$

the 2DEG Differential Mobility Sign-Ket Inverter $\boldsymbol{\sigma}$ exactly reproduces $|s\rangle$ (which thereby is proven to be an Eigenvector of the Operator $\boldsymbol{\sigma}$ under Conjugate Eigenvalue +1), the (Equiprobably-Superposed-Signs) $|s\rangle$ can be linked with the photodynamically evolutionary Crucial Incidence at which the 2DEG Differential Mobility momentarily vanishes ($\mathrm{d}\mu/\mathrm{d}\delta = 0|\delta = \Delta$).

4. Conclusions

Although significant research in 2DEG-based "Gatemon" Qubits has already been carried out (for example, [7] [8]) and, interestingly, Coherent Rabi Oscillations of such Qubits have been achieved between the pertinent Ground and First Excited Eigenstates, the Phenomenon of 2DEG Negative Differential Mobility has not, to our knowledge, been previously considered as prospectively conducive to some Qubit Functionality of the respective Nanosystem.

We, herewith, envisage that the Entity of the Effective Qubit emerging by virtue of the DMS of the Photodynamically Evolving Nanoheterointerfacial 2DEG might potentially support Quantum Information Registering: For example, Telecommunication Quantum Information Registering on the basis of a Train of Consecutive (cryptographically differing in Size and Arrival Timing) Photon-Packets being sent to the Nanosystem through an appropriate Optical-Fiber Waveguide.

We are, furthermore, intending to investigate the prospect of such a 2DEG DMS Qubit Functionality regarding the innovative THz-Photoluminescent Semiconductor Nanoheterointerface containing Two Communicating appropriately Asymmetric Quantum Wells [9].

Acknowledgements

Having been serving Hellenic University Physics for already 35 postdoctoral years, I remain eternally grateful to my original physics mystagogue, charismatic **Panagiotis Morphis**.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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