



# ON NEGATIVE DIFFERENTIAL MOBILITY IN NANOPHOTONIC DEVICE FUNCTIONALITY

EMMANUEL A. ANAGNOSTAKIS

*Hellenic Physical Society,  
174 55 Alimos, Greece  
emmanagn@otenet.gr*

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**Abstract:** The negative differential mobility (NDM) of two-dimensional carrier-gas against some proper external regulator allowing gradual controlled modification of the nanointerfacial environment tends to occur as interwoven with the nanophotonic device functionality. In this work, several instances from our two-decade principal research of both experimental observation and conceptual prediction concerning nanophotonics NDM are reconsidered towards outlining a global potential for the appearance of the effect.

**Keywords:** nanophotonics, two-dimensional electron-gas, semiconductor-device nanointerface, negative differential mobility, optoelectronics nanotechnology

## 1. Introduction

Photonics is underlain by absorption, emission, generation, handling, and exploiting light, typically within the electromagnetic radiation spectrum range between 100 nm of the ultraviolet and 1 000 nm of the infrared – with the human visual perception focused upon the 400–700 nm optical interval.

Nanophotonics, now, with its recently formulating disciplinary autonomy, traces, interprets, and envisions nanostructural spatial confinement – induced, often mystifying, modifications in light propagation and light-matter interaction. Nanophotonics, thus, is studying the essence and manifestations of confined electron de Broglie waves and confined light-wave photon flows. Interestingly enough, the function nanophotonic devices based on the GaN/GaAs, InAs/GaAs and InAs/InP materials-systems, nowadays adequately reach the middle infrared (mid-IR) regime between 370 and 1 600 nm.

Within the branch of electron-confinement nanophotonics, a crucial feature permeating semiconductor-nanodevice photonic functionality is the appearance of negative differential mobility (NDM) of the two-dimensional carrier-gas against



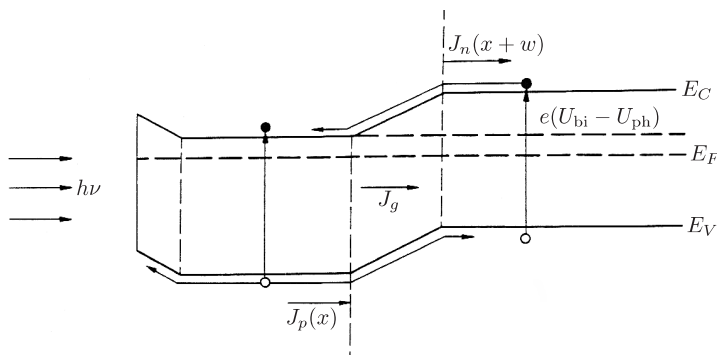
some proper external regulator (materialising as instantaneous cumulative photonic intake) allowing gradual controlled modification of the nanointerfacial environment.

In this work, several instances [1–20] from our two-decade principal research of both experimental observation and conceptual prediction concerning NDM are reconsidered towards outlining a global potential for the appearance of the effect, the essence of which consists in the variation of the mobility of nanointerfacial two-dimensional electron gas becoming negative against further positive proper regulatory change of the agent (bias, photonic dose) for some regulatory value-interval(s) of the agent.

## 2. NDM occurrence in nanophotonics homodevices

In Figure 1, the energy band depth-profile of a generic-homointerface nanophotonics device is presented: The band bending occurs at the illuminated  $n$ -type upper surface of the semiconductor layer and within the nanodevice interface extending between the equilibrium parts of this epilayer and the relatively  $p$ -type-like lower semiconductor-layer. The nanointerface (NIF) potential-energy barrier  $eU_b$  is equal to  $e(U_{bi} - U_{ph})$ , where  $U_{bi}$  is the NIF diodic built-in voltage and  $U_{ph}$  is the generated evolving photovoltage [2–4, 7]. The photocurrent density  $J$  through the NIF consists of the space-charge – region photogeneration-current density  $J_g$ , the current density  $J_p(x)$  at the NIF upper-boundary locus  $x$  owing to the hole diffusion from the  $n$ -type epilayer downwards, and the current density  $J_n(x+w)$  at the NIF lower-boundary locus  $x+w$  owing to the electron diffusion from the  $p$ -type sublayer upwards [1].

Experimental findings for mean electron-mobility  $\langle\mu\rangle$  (in  $10^2 \text{ cm}^2/(\text{Vs})$ ) within the  $n$ -type (Si-ion implantation) epilayer of representative photonics NIF-devices [1, 9, 12] *vs.* incoming instantaneous cumulative photon-dose  $\delta$  (in photons/ $\text{cm}^2$ ) have been discussed in previous works of ours: The functional feature of negative differential mobility (NDM) is being registered from the mobility



**Figure 1.** Energy band depth-profile of a generic-homointerface nanophotonics device: The nanointerface (NIF) potential-energy barrier  $eU_b$  is equal to  $e(U_{bi} - U_{ph})$ , where  $U_{bi}$  is the NIF diodic built-in voltage and  $U_{ph}$  is the generated evolving photovoltage

peak (at total photonic intake  $\delta_{\text{peak}}$  of around  $1 \cdot 10^{11}$  photons/cm<sup>2</sup>) to the mobility valley (at cumulative photon dose  $\delta_{\text{valley}}$  of around  $4.64 \cdot 10^{12}$  photons/cm<sup>2</sup>). Each instantaneous value of the average mobility is determined within the respective instantaneous extension of the photo-widening flat-band portion of the epilayer through the experimentally measured (mean) sheet electron conductivity ( $\sigma d$ ) and (mean) sheet electron concentration ( $nd$ ) of this flat-band epilayer extension by  $\langle \mu \rangle = (\sigma d)/(nd)$ . The local mobility  $\mu$ , furthermore, at the instantaneous NIF-boundary locus  $x$  is interplaying with the mean mobility  $\langle \mu \rangle$  and the dose-rates  $u$  and  $v$  of the evolution of ( $\sigma d$ ) and ( $nd$ ), respectively, according to the causal correlation [1, 9, 10, 12]:

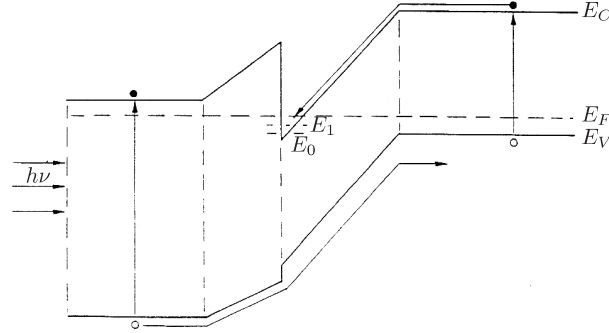
$$v = \frac{u}{e\langle \mu \rangle^2} (2\langle \mu \rangle - \mu) \quad (1)$$

with  $e$  being the absolute value of the electron charge.

### 3. NDM occurrence in nanophotonics heterodevices

In Figure 2 the energy band depth-profile of a generic-heterointerface nanophotonics device is sketched: The front, wider-bandgap,  $n$ -type semiconductor-layer is succeeded by a lower, narrower-bandgap, relatively  $p$ -type-like. The NIF, now, hosts the ionized-donor depletion zone, on the epilayer side, and the potential-energy, approximately triangular, QW, formed within the sublayer's upper part. The photocurrent density  $J$  through the NIF comprises the current density  $J_g$  produced by photogeneration within both the ionized-donor depletion-zone and the QW, the current density  $J_p(x)$  at the NIF upper-boundary locus  $x$  owing to the hole diffusion from the  $n$ -type epilayer downwards, and the current density  $J_n(x+w+L)$  at the NIF lower-boundary (deeper by the consecutive extensions  $w$  and  $L$  of the depletion zone and the QW) locus  $x+w+L$  owing to the electron diffusion from the  $p$ -type sublayer upwards [3, 5, 7, 8]. The onset of the occupancy of the first excited QW-subband (of bottom energy  $E_1$ ) occurs as soon as the two-dimensional electron gas (2DEG) population already confined within the NIF QW energy-wise span the interval  $\Delta E = Z_0/\rho$ , from the QW fundamental-subband bottom onwards, with  $Z_0$  constituting the capacity of the fundamental subband and  $\rho$  being the parabolic-model two-dimensional density of states (with respect to the energy graduation and QW-bottom cross-section interval). An effective harmonic oscillator simulating the prime functionality of the NIF QW leads to a simple, yet notionally adequate and rather universal, NIF descriptor  $\Gamma = L\Omega$ , with  $\Omega$  being the simulative-oscillator strength, shown to be expressible in terms of the carrier effective mass and the entailed-nanoheterojunction conduction-band discontinuity as  $\Gamma = 2(2\Phi/m^*)^{1/2}$ .

The reduced (over dark value  $\mu_d$ ) persistent photoenhancement (PPE) ( $\Delta\mu/\mu_d$ ) in the 2DEG mobility  $\mu$  has been experimentally registered *vs.* relative (with respect to a nanodevice-specific value  $\delta^*$ ) total photonic intake ( $\delta/\delta^*$ ), for representative nanophotonics (modulation-doping) heterointerface-devices of previous studies of ours [3, 5, 7, 8, 14, 16, 17] (based on a typical molecular-beam epitaxy Si:Al<sub>0.3</sub>Ga<sub>0.7</sub>As/GaAs nanoheterodiode mounted upon a semi-insulating



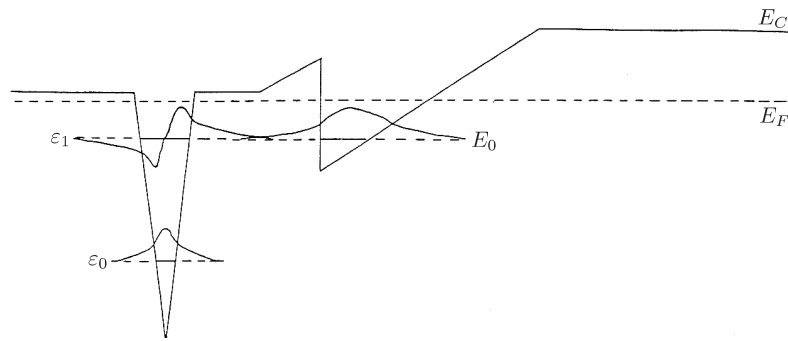
**Figure 2.** Energy band depth-profile of a generic-heterointerface nanophotonics device: The NIF, now, hosts the ionized-donor depletion zone, on the epilayer side, and the potential-energy, approximately triangular, QW, formed within the sublayer's upper part

GaAs substrate): The NIF 2DEG mobility PPE  $\Delta\mu$  is increasing up to a critical relative cumulative photon-dose value  $(\delta/\delta^*)_{crit}$  of the order of  $4.79 \cdot 10^2$  and then it is dropping, a NDM ( $[d(\Delta\mu)/d\delta] < 0$ ) regime being marked, tantamount to the process of occupancy of the first excited NIF QW subband, following the saturation of the capacity  $Z_0 = 1.01 \cdot 10^{12}$  electrons/cm<sup>2</sup> (as determined through the experimentally traced photon-dose – evolution of the 2DEG sheet concentration  $\zeta$ , observed at the above critical total photonic intake) of the fundamental subband. The energy separation  $\Delta E$ , now, between the nominal bottoms of these successive NIF QW subbands is (through the capacity of fundamental one) deduced to be of 35.3 meV, leading to a simulative harmonic oscillator's strength  $\Omega$  of  $5.354 \cdot 10^{13}$  s<sup>-1</sup> yielding (through the NIF descriptor value  $\Gamma = 1.168 \cdot 10^6$  m/s valid for the pertinent QW-electron effective mass and conduction-band discontinuity) a 2DEG-QW effective spatial width  $L$  of 21.8 nm.

#### 4. NDM interweaving with nanophotodevice operational principle

In Figure 3, the conduction-band depth-profile of the nanophotonics launcher – receptor quantum electron-device (LRD) appears, proposed in 1994 [11] as a vertical-transport optoelectronic nanodevice relying upon resonant quantum-mechanical electron-tunnelling from a charge-launcher element (CLE) into a charge-receptor pocket (CRP) within an illuminated NIF semiconductor-heterostructure. In a model visualization, the LRD comprises an Al<sub>0.22</sub>Ga<sub>0.78</sub>As epilayer hosting a narrow (around 3 nm)  $\delta$ -spike of high (especially with respect to background doping) sheet-density (of the order of  $2.0 \cdot 10^{12}$  donors/cm<sup>2</sup>) Si dopants as the photonic nanodevice CLE and a non-intentionally doped GaAs underlayer containing nanoheterointerfacial 2DEG-QW (of spatial width of the order of 20 nm, adjacent to the ionized – background-donor depletion-zone of the epilayer side) as the nanostructure CRP. Functionally strategic energy-matching between the CLE first excited sublevel  $\varepsilon_1$  and the CRP fundamental sublevel  $E_0$  at around 50 meV below the LRD Fermi level is attained, allowing the possibility of resonant quantum-

mechanical tunnelling of a part of first-excited-subband CLE-electron population (present there after the saturation of the local fundamental subband’s capacity, at a critical cumulative photonic intake during the persistent-photoenhancement experimental procedure) into the fundamental CRP-QW subband. Such an optoelectronic nanoswitching functionality would, then, be permeated by incidents of NDM owing to an appropriate timing for the energising of different individual effective-mobility values [5, 11, 16, 17, 19] (via varying subband curvatures and scattering environments) characterising conductively interplaying subbands.

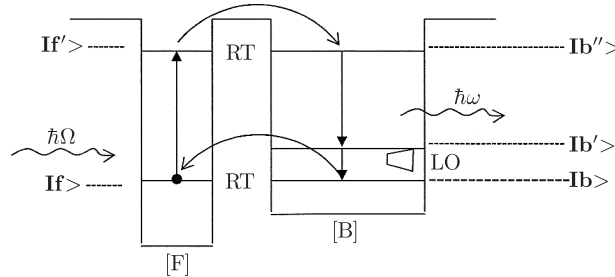


**Figure 3.** Conduction-band depth-profile of the nanophotonics launcher – a receptor quantum electron-device (LRD), proposed in 1994 as a vertical-transport optoelectronic nanodevice relying upon resonant quantum-mechanical electron-tunnelling from a charge-launcher element (CLE) into a charge-receptor pocket (CRP) within an illuminated NIF semiconductor-heterostructure. Such an optoelectronic nanoswitching functionality would, then, be permeated by incidents of NDM owing to an appropriate timing for the energising of different individual effective-mobility values (via varying subband curvatures and scattering environments) characterising conductively interplaying subbands

### 5. NDM tractability via nanophotonics wavefunction-engineering

In Figure 4, furthermore, the wavefunction-engineering of a THz-LASER nanophotonics device proposed in 2010 [18] is outlined: The optically pumped dual – resonant-tunnelling LASER-action unipolar-charge – transport mechanism is simulatively onset for an indicative generic semiconductor nanoheterostructure based on the conventional  $Al_xGa_{1-x}As/GaAs$  material system.

In particular, two totally asymmetric – both in the spatial width and in the energetic barrier height – communicating through an intervening barrier layer, approximately rectangular quantum wells, both formulated within (different portions of) the GaAs semiconductor are employed: The front QW [F] of spatial width 96 Å and energetic barrier height 221 meV, contained between the surface  $Al_{0.3}Ga_{0.7}As$  slab and the inter – QW communication barrier layer, and the back QW [B] of growth axis extension 162 Å and energetic confinement hill 204 meV, spanning the region between the inter – QW communication barrier layer and a bottom  $Al_{0.33}Ga_{0.67}As$  slab. The intervening, inter – QW communication



**Figure 4.** Wavefunction-engineering of a THz-LASER nanophotonics device proposed in 2010: The optically pumped dual – resonant-tunnelling LASER-action unipolar-charge – transport mechanism is simulatively energised for an indicative generic semiconductor nanoheterostructure based on the conventional  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$  material system

barrier layer may non-exclusively be regarded as the succession (either abrupt or graded) of two rather equithick sublayers of  $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  and  $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$ . It is, then, algorithmically determined (through *Quantum-Well Tridiagonal Algorithm* [20]) that the partially localised conductivity electron eigenstates accommodated by the couple of communicating QWs in the model application under study correspond to the energy eigenvalues (measured within each QW from its energetic bottom upwards):  $E(\text{If}) = 32\text{ meV}$ ,  $E(\text{If}') = 136\text{ meV}$  – for the front QW fundamental and first excited bound state, respectively, – and  $E(\text{Ib}) = 14\text{ meV}$ ,  $E(\text{Ib}') = 55\text{ meV}$ , and  $E(\text{Ib}'') = 121\text{ meV}$  – for the back QW fundamental, first excited, and second excited bound state, respectively.

Notably, against this predicted energy eigenvalue configuration, the fundamental back QW eigenstate  $\text{Ib}$  elevated by  $14\text{ meV}$  over the back QW energetic bottom finds itself well aligned with the conjugate fundamental eigenstate  $\text{If}$  of the front QW raised above its QW energetic bottom by an amount corresponding to the inter – QW energetic bottom discrepancy plus, about, the former fundamental eigenstate  $\text{Ib}$  height over its local QW bottom. In an analogous manner, the uppermost bound eigenstates of the two communicating QW, emerge aligned, as the difference in the height of each over its local QW bottom almost cancels the energetic height asymmetry of the two QW bottoms.

The determinable intersubband transition (ISBT) effective dipole lengths, furthermore, demonstrate the oscillator strengths supporting the different ISBT events, whereas the LASER action population inversion predicted would lead to the device stimulated optical gain.

The notional and functional framework, furthermore, of the principle of operation of such an intersubband THz-LASER nanophotonics device provides fruitful ground [5, 14–16] for the prediction, monitoring, and registration of NDM features marking incidents of local transition and resonant-tunnelling vertical transport, the essence of the innovation of a nanophotonics launcher – receptor quantum electron-device (LRD) [11] getting recapitulated and through such modelling advanced and generalised.

## 6. Conclusion

Several instances from our two-decade principal research of both experimental observation and conceptual prediction concerning nanophotonics NDM have been reconsidered towards outlining a global potential for the appearance of the effect, the technological importance of the NDM crucial feature envisaged to be emerging.

It is worth mentioning that a global potential for the manifestation of NDM would be the nanophotonic device's capacity for simultaneously supporting subsets of the interfacial conductivity-carrier ensemble through distinctly mobility-valued mechanisms.

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