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ON A NANOPHOTONIC RESPONSE DESCRIPTOR

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Abstract: The photonic response exhibited by typical semiconductor nanodevices is modeled through a notionally universal descriptor by virtue of the Green's function associated with the generic complete, inhomogeneous differential equation. It is derived that the photoresponse evolution is expressible as the sum of saturation-limiting linear nanophotonic behavior and a linear superposition of eigenfunctions of the respective homogeneous Fredholm integral equation.

Keywords: nanodevices, photonic response, optoelectronics, nanophotonics, Green's function, Fredholm kernel

1. Introduction

The motivation for this study derives from the experience of systematical investigating of the photonic response of semiconductor diodic nanodevices for two decades already [1]: Their (persistent) conductivity enhancement behavior under evolving cumulative photonic intake proves [2–4] crucial for their technological applicability such as, *inter alia*, swift optoelectronic switches, exact photon counters and reliable telecommunication transducers.

Both prediction and interpretation of their functionality through codification of a notionally universal descriptor commensurate with their experimentally monitored nanophotonic fundamental parameters as well as their asymptotic photoenhancement steady state seem worth attempting.

A typical nanophotonic response concerns the evolution of the nanodevice persistent photocarrier sheet density η against the instantaneous cumulative photon dose β absorbed. This paper follows the procedure up to the occurrence of the negative differential mobility feature linked to the onset of the occupancy of the nanoheterojunction first excited conduction subband.

2. Nanophotonic response modeling

In previous studies of ours, an approximate analogy between the photonic dose β rate of change $(d\eta/d\beta)$ of the persistent photocarrier sheet density η and the average conductivity carrier mobility μ [1] has been traced allowing the expression of the second photonic dose derivative $\eta''_{\beta\beta}=(d^2\eta/d\beta^2)$ of the surface concentration η as a nanodevice-specific multiple of the photonic dose rate of change $\mu'_\beta=(d\mu/d\beta)$ of carrier mobility μ:

$$\eta''_{\beta\beta}+M\mu'_\beta=0,\quad M<0 \tag{1}$$

Equation (1) already incorporates the experimentally monitored limiting linearity of $\eta(\beta)$ for approaching the saturation of the nanophotonic device fundamental conduction subband, signaled by the instantaneous vanishing of μ'_β.

The physically meaningful boundary conditions reflect that the photoinduced electron surface concentration scans the scale from its naught dark-value to the capacity η_0 of the eventually (at critical total photonic dose β_0) saturated fundamental subband:

$$\eta(0)=0\quad\text{and}\quad\eta(\beta_0)=\eta_0 \tag{2}$$

Mathematically, the solution of Equation (1) under the inhomogeneous boundary conditions (2) is formulated as the superposition of function $\chi(\beta)$ satisfying the respective homogeneous differential equation:

$$\chi''_{\beta\beta}=0 \tag{3}$$

subject to the inhomogeneous terminal conditions:

$$\chi(0)=0\quad\text{and}\quad\chi(\beta_0)=\eta_0 \tag{4}$$

and function $\psi(\beta)$ verifying the complete, inhomogeneous differential equation:

$$\psi''_{\beta\beta}+M\mu'_\beta=0 \tag{5}$$

under the associated homogeneous terminal conditions:

$$\psi(0)=0\quad\text{and}\quad\psi(\beta_0)=0 \tag{6}$$

Obviously, the particular solution of Equation (3) consistent with the requirement (4) is:

$$\chi(\beta)=\eta_0(\beta/\beta_0) \tag{7}$$

On the other hand, for complete Equation (5) holding under conditions (6) the respective Green's function $g(\beta,\gamma)$ may be employed which for a reference cumulative photonic dose γ reads:

$$g(\beta,\gamma)=-B(\beta)\Gamma(\gamma)/w[B,\Gamma]_\gamma\quad\text{for}\quad\beta<\gamma \tag{8}$$

$$g(\beta,\gamma)=-B(\gamma)\Gamma(\beta)/w[B,\Gamma]_\gamma\quad\text{for}\quad\beta>\gamma \tag{9}$$

with $B(\beta)$ being the solution of the homogeneous equation:

$$B''_{\beta\beta} = 0 \tag{10}$$

under the condition

$$B(0) = 0 \tag{11}$$

$\Gamma(\gamma)$ being the solution of the homogeneous equation:

$$\Gamma''_{\beta\beta} = 0 \tag{12}$$

under the condition

$$\Gamma(\beta_0) = 0 \tag{13}$$

and $w[B,\Gamma]_\gamma$ being the Wronskian determinant of functions B and Γ evaluated at the reference instantaneous cumulative photonic dose γ.

Thus, the Green's function takes the form:

$$g(\beta,\gamma) = (\beta_0 - \gamma)\beta/\beta_0 \quad \text{for} \quad \beta < \gamma \tag{14}$$

$$g(\beta,\gamma) = (\beta_0 - \beta)\gamma/\beta_0 \quad \text{for} \quad \beta > \gamma \tag{15}$$

Upon the above, the solution of Equation (5) consistent with conditions (6) is derivable as the convolution between the Green's function g and the stimulus $M\mu'_\beta$:

$$\psi(\beta) = {}_0[g(\beta,\gamma) * M\mu'_\beta(\gamma)]_0^\beta \tag{16}$$

3. Nanophotonic response descriptor

In the light of the fact that the modeling scheme Green's function is nanodevice-specific as parameterized by the characteristic total photonic dose β_0 tantamount with the saturation of the capacity η_0 of its fundamental conduction subband, it appears meaningful to adopt $g(\beta,\gamma)$ as a potentially notionally universal nanophotonic response descriptor (NRD).

Owing to the symmetry of the NRD with respect to interchanging its two arguments β and γ, $\psi(\beta)$ being generated by the convolution between the continuous, real-valued, symmetric, double argument function $g(\beta,\gamma)$ and the continuous, real-valued, single argument function $M\mu'_\beta(\beta)$, determined by the nanophotonic nature of the experimental device and its measured $\mu'_\beta(\beta)$ photoresponse, can be represented [5] by a linear combination (through a series κ_ν of pertaining weighting coefficients) of the eigenfunctions $\psi_\nu(\beta)$ of the homogeneous Fredholm integral equation having the particular double argument function $g(\beta,\gamma)$ as its kernel:

$$\psi(\beta) = \Sigma_\nu\{\kappa_\nu\psi_\nu(\beta)\} \tag{17}$$

with $\psi_\nu(\beta)$ being the ν-th order eigenfunction of the homogeneous Fredholm (convolution) integral equation:

$$\psi_\nu(\beta) = \alpha_\nu\, {}_0[g(\beta,\gamma) * \psi_\nu(\gamma)]_0^\beta \tag{18}$$

with α_ν denoting the respective ν-th order real eigenvalue (fulfilling the property that a pair of mutually orthogonal eigenfunctions) and the NRD embodying the Fredholm kernel correspond to each pair of distinct eigenvalues.

Therefore, $\psi(\beta)$ is derived through Equation (17) as the resultant of the orthogonal component eigenfunctions $\psi_\nu(\beta)$ as scaled by the appropriate real coefficients κ_ν determined through the photoenhancement-associated stimulus function $M\mu'_\beta(\beta)$ energizing the nanophotonic device under experimental monitoring.

4. Conclusions

Initiation of the herewith conceived and discussed NRD is expected to be proving conducive to useful conclusions with respect to current and future photonic investigations of (hetero)junction nanodevices:

Firstly, the availability of a notional scheme allowing consideration of the instantaneous nanophotonic response of a semiconductor device as the functional superposition of inherent limiting performance and a dynamic interplay of synergy eigenfunctions permeated by measurable parameters of an individual nanodevice.

Secondly, the conceptual and computational isomorphism of the NRD ingredients (Fredholm eigenfunctions, superposition weighting factors) to the nanodevice energy band structure and majority carrier mobility photoenhancement evolution idiosyncrasy.

Thirdly, the inspirational virtue of the introduced NRD to permit guidance of Wavefunction-Engineering of the operation of future nanophotonic devices which would be exhibiting pre-chosen (in accordance to pre-evaluation of the NRD parameters) application-specific Figures of Merit (mean photonic dose rate of reaching the nanodevice fundamental subband capacity).

In the present paper a notionally universal nanophotonic response descriptor has been adopted in terms of the kernel of the Fredholm integral equation providing the orthogonal spectrum attached to the limiting behavior for causally picturing the complete nanophotonic response function of a typical semiconductor heterojunction device.

References

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