Nonlinear dynamics of recharging processes in multiple quantum well structures excited by infrared radiation

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We study the spatiotemporal variations of electric-field distributions in multiple quantum well structures excited by infrared radiation due to bound-to-continuum electron transitions using ensemble Monte Carlo particle simulations. The occurrence of self-sustained pulsing and the formation of spatially periodic electric-field domains with weakly oscillating amplitudes demonstrated in the simulations are associated with the excitation of the recharging waves. It is shown that the dynamics of electric-field distributions and photocurrent can be different in the structures with even and odd numbers of quantum wells.

I. INTRODUCTION

Electron phenomena in semiconductor heterostructures with a large number of uncoupled or scarcely coupled quantum wells (QW's) have been the topic of extensive experimental and theoretical studies[1] (see also references therein). This, in part, is due to a wide interest in QW infrared photodetectors (QWIP's) utilizing intersubband bound-to-continuum (bound-to-bound) electron transitions. Despite the relatively simple structure of a QWIP, the physics of the processes responsible for its operation is fairly complex. Such processes include the intersubband transitions accompanying the electron thermoemission, photoexcitation, and capture, the tunneling injection of electrons from the emitter contact, strongly nonequilibrium transport of the electrons excited to continuum states in the self-consistent electric field, and, finally the collection of electrons by related contact. In contrast to the structures with coupled QW's in which the electron current is due to sequential tunneling or miniband transport,[2–11] in the QW structures used in QWIP's, electrons propagate primarily over the continuum states above the interwell barriers.[1] Several physical models using both analytical and numerical simulation approaches have been proposed for steady-state and transient operation of QWIP's.[12–25] Early models of QWIP's with multiple QW's assumed that the electric-field distribution in the active region is uniform.[12,13] Later, it has been shown that the space charge gives rise to the nonuniformity of the electric field either near the emitter contact[15,17,19–21] or spread across the whole structure.[18] Some features of the QWIP characteristics were attributed to the occurrence of high- and low-field domains.[19]

Very recently the formation of periodic electric-field and charge domains in QW structures excited by infrared radiation has been predicted in our Monte Carlo (MC) simulations.[26,27] As it has been shown, contrary to the previous assumptions that the electric-field distributions, even being nonuniform, are relatively smooth and monotonic, stable periodic electric-field structures with a period equal to twice the spacing between QW's can occur. The occurrence of periodic domains is attributed to the excitation of the waves of QW recharging similar to those in compensated semiconductors with deep traps.[28,29] The excitation of recharging waves in QW structures is due to the instability of smooth monotonic electric-field distributions with respect to the perturbations in which different QW's are charged differently.[26,27,30] The formation of stable periodic electric-field domains is accompanied by strong spatiotemporal variations of the electric field and pronounced pulsing of the photocurrent.

Here we present the results of MC simulations of nonlinear electric-field and current oscillations in multiple QW structures with doped uncoupled QW's irradiated by infrared radiation stimulating the electron bound-to-continuum intersubband transitions. We show that depending on the parity of the number of QW's, the periodic domains are formed either immediately upon the completion of transient process (in the structures with odd numbers of QW's) or after a long stage of strong chaotic pulsations (when the numbers of QW's are even). In both cases, the spatial amplitude of the established periodic electric-field domains exhibits temporal oscillations. However, the swing of such oscillations is much smaller than that of the oscillations before the domain formation. The features of the recharging dynamics studied favors the chaotic nature of the latter. The QW structures under consideration are similar to those used in QWIP's. Hence, the obtained results can be beneficial for an in-depth understanding of physical processes in these devices, particularly those operating at high-power excitation levels.

II. MODEL

We consider n-type $Al_{0.22}Ga_{0.78}As/GaAs$ multiple QW structures with doped QW's separated by relatively thick undoped barrier layers. The QW structures are supplied by contact regions made of a doped narrow-gap material. Due to large barrier thicknesses, the tunneling of electrons between QW's is neglected, hence, the vertical electron transport across the structure is associated with the propagation of electrons above the barriers. However, the electron injection from the emitter contact is due to tunneling through the top of the first (emitter) barrier in the structure. The density of injected current j is determined by the electric field in this barrier E_e: $j = j_m \exp[-(E_t/E_e)]$, where j_m is the maximum current density provided by the emitter contact and E_t is the characteristic tunneling field.

The intensity of incident infrared radiation I is assumed to be high enough, so that the rate of QW photoionization $G_n = \sigma \Sigma_n I$, significantly exceeds the rate of thermionic emission from QW's. Here n is the QW index ($n = 1,2, \ldots ,N$, where N is the number of QW's in the structure), σ is the cross section of the electron photoescape from a QW, and Σ_n is the electron sheet concentration in the nth QW.

We study the nonequilibrium electron system in QW structures under the influence of infrared radiation in the framework of an ensemble MC particle method described previously.[26,27] The MC model used for the calculations takes into account the features of the material band structures and all significant scattering mechanisms, including the electron reflection from the QW-barrier heterointerfaces. The electron capture is considered as the transition of an electron from the continuum states above the barriers into the bound states accompanied with the optical-phonon emission.[31–33] The interaction of Γ electrons with QW's is described as their reflection, transmission, or capture with the probabilities calculated quantum mechanically.[34] The transport of L and X electrons is considered classically.

The self-consistent electric potential (field) obeys the Poisson equation

$$\frac{d^2\varphi}{dx^2} = \frac{4\pi e}{æ}\left[\sum_{n=1}^{N}(\Sigma_n - \Sigma_d)\,\delta(x - nL) + \rho - \rho_d\right] \quad (1)$$

with the following boundary conditions:

$$\varphi|_{x=0} = 0 \quad \text{and} \quad \varphi|_{x=W} = V, \quad (2)$$

where e is the electron charge, æ is the dielectric constant, ρ is the concentration of electrons above the barriers, Σ_d and ρ_d are the donor sheet concentration in QW's and the donor concentration in the barriers, respectively, $L = L_w + L_b \simeq L_b$ is the QW structure period, L_w and L_b are the thicknesses of the QW and the barrier, $\delta(x)$ is the QW form factor, which is assumed to be similar to the Dirac δ function (due to $L_w \ll L_b \simeq L$), $W = NL_w + (N+1)L_b$ is the net thickness of the QW structure, V is the applied bias voltage, and x is the coordinate in the direction perpendicular to the QW plane.

To eliminate statistical problems inherent in ensemble MC particle simulations, the quality of the randomizer used in the MC procedures was specially checked and the time step and the mesh size were chosen sufficiently small, corresponding to 10 fs and 2 nm, respectively. The number of particles (electrons) used in simulations was up to 150 000 depending on the applied voltage and the number of QW's.

The initial momentum distributions of the injected and photoexcited electrons are determined by the emitter barrier (modified under the effect of electric field) and by the difference between photon energy $\hbar\Omega$ and ionization energy of QW's ϵ_i, respectively. The collector contact absorbs all electrons passed the last barrier.

The spatiotemporal distributions of the concentrations of bound and mobile electrons and the electric field obtained employing MC procedures and Eq. (1), are used to calculate macroscopic characteristics of QW structures, in particular, the photocurrent.

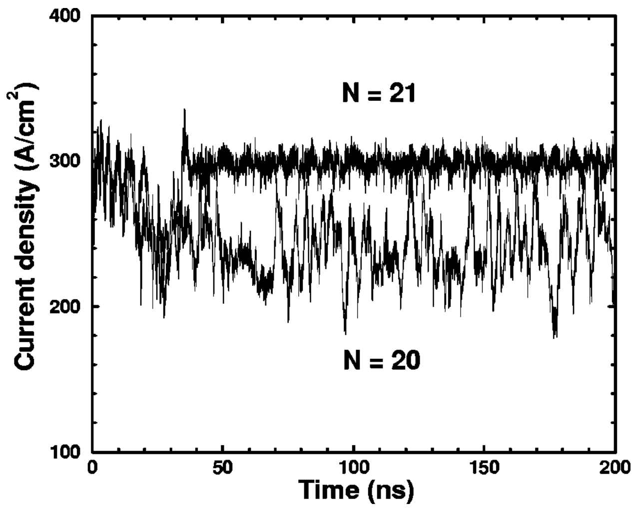

FIG. 1. Transient photocurrent in response to a steplike infrared pulse in the structures with 20 and 21 QW's.

The QW structure parameters utilized in the calculations are as follows: the number of QW's $N = 4-21$, the QW structure period $L = 52$ nm ($L_w = 4$ nm and $L_b = 48$ nm), the barrier donor concentration $\rho_d = 10^{14}$ cm^{-3}, the QW donor sheet concentration $\Sigma_d = 10^{12}$ cm^{-2}, the maximum emitter current density $j_m = 1.6\times 10^6$ A/cm^2, and the emitter tunneling field $E_t = 340$ kV/cm. The photoescape cross section, average initial energy of photoexcited electrons, and intensity of radiation were assumed to be $\sigma = 2\times 10^{-15}$ cm^2, $\Delta = \hbar\Omega - \epsilon_i = 10$ meV, and $I = 10^{23}$ cm^{-2} s^{-1}, respectively. The applied voltages were chosen to provide the average electric field in the structure $E = V/W = 15$ kV/cm. All simulations correspond to the liquid-nitrogen temperature ($T = 77$ K).

III. RESULTS

We followed the response of QW structures with different parameters at different applied voltages to steplike pulses of infrared radiation: $I(t) = I\Theta(t)$, where $\Theta(t)$ is the unity step function. The initial states corresponded to nearly uniform electric-field distributions with neutral QW's.

Figure 1 shows the transient photocurrent in QW structures with $N = 20$ and 21. The temporal variations of the electric fields in the fifth and sixth barriers of these structures are shown in Fig. 2. As seen from Figs. 1 and 2, the structures with such a small difference in the numbers of QW's exhibit substantially different transient behavior. In the QW structure with 21 QW's, the photocurrent and the electric fields in different barriers are established upon a relatively short period of time (about 50 ns). Typical electric-field distributions in the structures under consideration are shown in Fig. 3. The establishment of photocurrent in the structure with $N = 21$ is accompanied by the formation of stable periodic electric-field domain (see Fig. 3). Both the established photocurrent and electric field include time-independent components modulated by low-amplitude undamped oscillations. These oscillations appear to be chaotic. Their amplitude being small compared to the spatial periodic variations pronouncedly exceeds the level of statistical fluctuations. The occurrence of spatially periodic electric-field domains

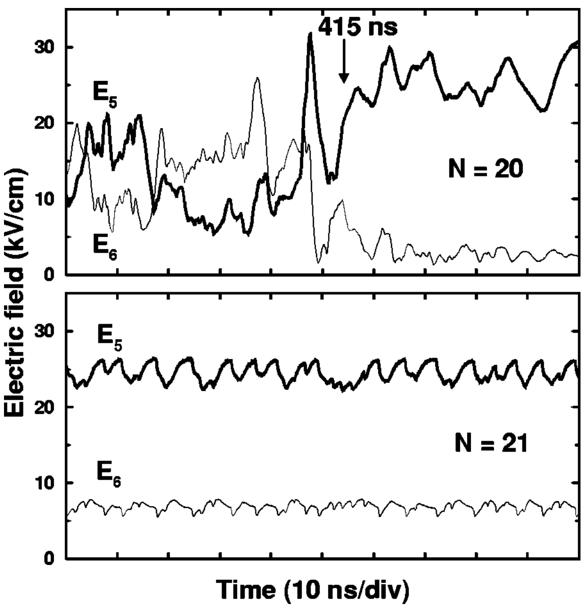

FIG. 2. Temporal variations of the electric fields in fifth and sixth barriers in the structures with 20 and 21 QW's.

with the period equal to double the period of the QW structure with $N=21$, is the manifestation of the direct development of the excited recharging waves.

In contrast to this, the photocurrent and the electric-field distributions in the structure with 20 QW's did not show any trend to the establishment of stationary or even near stationary states demonstrating strong self-sustained pulsations for rather long time (up to $t \simeq 400$ ns). This can be attributed to the excitation of several modes of large amplitude recharging waves.[26,27,30] At $t \simeq 415$ ns the behavior of the 20 QWth structure suddenly changed (see Fig. 3) with the transition from the spatiotemporal oscillations with strongly fluctuating ratio of the electric fields in the neighboring barriers to spatially nearly periodic electric-field structure with high-electric field in odd-numbered barriers and low-electric field in even-numbered ones (see the electric-field structures for $N=20$ corresponding to $t=200$ and 500 ns in Fig. 2). The amplitude of the formed periodic structure is modulated akin to that in the structure with $N=21$. The transition from a strongly pulsing state to a more or less calm and spatially ordered one is accompanied by a pronounced reduction in the averaged photocurrent density (from about 250 to 150 A/cm^2).

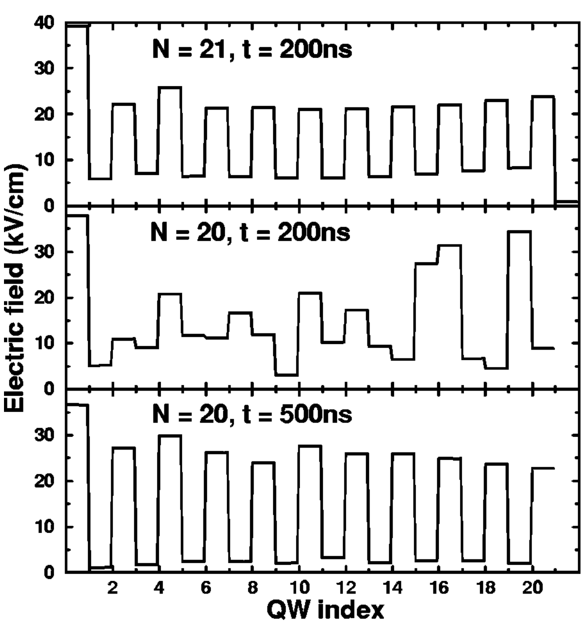

FIG. 3. Spatial distributions of the electric field in the structures with 20 and 21 QW's at different moments.

Similar spatiotemporal oscillations of the electric field were found also in the structures with some other even numbers of QW's (with $N=12$, 14, and 18). For even-numbered N, the formation of periodic electric-field domains via a strongly irregular stage, requires essentially a longer period of time (nearly ten times longer) than the formation of such domains when N is an odd number. When N is an odd number, the evolution of the electric-field distribution usually gives rise to relatively fast formation of periodic domains with period $2L$. One may suggest that the parity of the number of interwell barriers promotes the occurrence of periodic electric-field distributions. This is because in the case of an even number of the barriers, boundary conditions (2) are automatically satisfied for periodic spatial distribution of the electric field. Indeed, taking into account that in the cases under consideration, the space charge of mobile electrons and donors in the barriers is negligible compared to the charges of QW's, and, hence, the electric fields in the barriers E_n are uniform; from conditions (2) one can obtain

$$\sum_{n=1}^{N+1} E_n = (N+1)E. \tag{3}$$

Consequently, if $(N+1)$ is an even number, any periodic electric-field distribution with $\delta E_n = -\delta E_{n+1}$, where $\delta E_n = E_n - E$, satisfies Eq. (3). For near periodic distributions this equation can be satisfied by a slight adjustment of the amplitudes of spatial variations. Once the number of barriers $(N+1)$ is odd one, the development of periodic perturbations at the linear stage is forbidden while the formation of periodic domains at later stages is hampered by the occurrence of relatively long recharging waves.

The structures with even numbers of QW's exhibit a markedly larger swing of the spatial variations of the electric field and large electric field in the barrier adjacent to the collector contact than those with odd numbers of QW's. As follows from Eq. (3), the occurrence of near periodic distributions with a strong electric field in the collector barrier is possible if the spatial variations of electric field throughout the QW structure are sufficiently large to compensate the imbalance caused by the potential drop in this (odd numbered) barrier.

It is worth noting that in QW structures with sufficiently small number of QW's ($N=4-11$) in all cases investigated in our simulations, the nonlinear development of recharging waves resulted in relatively fast formation of periodic (or near periodic) electric-field domains disregarding the parity of number $(N+1)$. This can be explained by the effect of emitter contact suppressing long-wave excitation in QW structures with small or moderate N. Conversely, in QW structures with a very large number of QW's, one may expect that the restrictions imposed by both the fixation of the

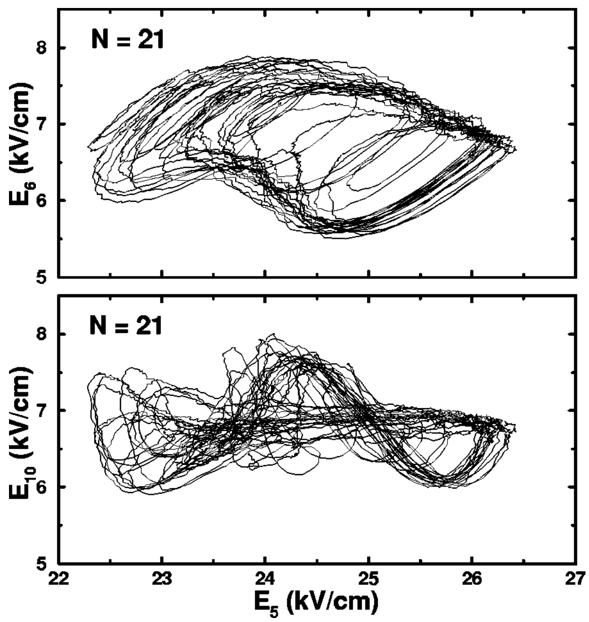

FIG. 4. Phase-space attractors, constructed from time series (400 ns$\leqslant t \leqslant$500 ns) for the electric fields in two neighboring (fifth and sixth barriers) and two far-away (fifth and tenth) picked arbitrary barriers in the structure with 21 QW's.

voltage drop between the contacts and the effect of the emitter contact are lifted, so that the formation of periodic domains becomes independent of whether N is an even or odd number.

The observed pulsations of the electric-field distributions and the photocurrent both at the initial stage and upon the formation of periodic structures resemble chaotic one's.[35,36] To find arguments in favor of the chaotic nature of the electric-field distributions behavior, we constructed the phase-space attractors using the calculated temporal dependencies of the electric fields in different barriers in QW structures with different numbers of QW's shown in Figs. 4–6. These figures correspond to the period of time from the moment when the transitive processes, triggered by the turning on of infrared irradiation, were terminated to the distant moment, more specifically from $t=400$ to 500 ns. This period is much longer than the characteristic times[26,27,30] responsible for different electron processes in the structure. As seen from Figs. 5 and 6, the transition from the state with large amplitude variation of the electric field to a more calm spatially ordered state, coincides with a change in the trajectories in phase space. Figure 7 shows the phase portrait for the electric field in the fifth barrier (dE_5/dt vs E_5) in the structure with 20 QW's, which can be interpreted as supporting the hypothesis on chaotic behavior of the electron system in the QW structures under consideration. The main distinction between the trajectories before and after the transition is a pronounced difference in the swing of oscillations. The periodic electric-field distribution formed in the structure with 20 QW's resembles that in the structure with 21 QW's (see Fig. 3), although their phase-space attractors exhibit some distinctions seen from the comparison of Figs. 4, 5, and 6.

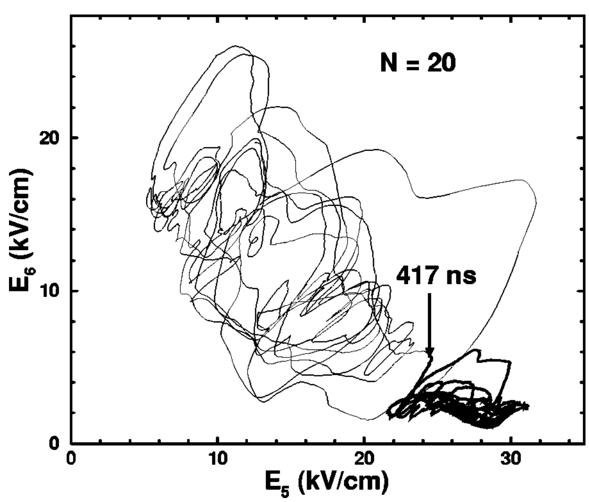

FIG. 5. Phase-space attractors, constructed from time series (400 ns$\leqslant t \leqslant$500 ns) for the electric fields in fifth and sixth barriers in the structure with 20 QW's. The thick curve corresponds to the moments of time $t \geqslant 417$ ns, i.e., after the transition from large amplitude chaotic oscillations to chaotic oscillations of amplitudes of established periodic electric-field structure.

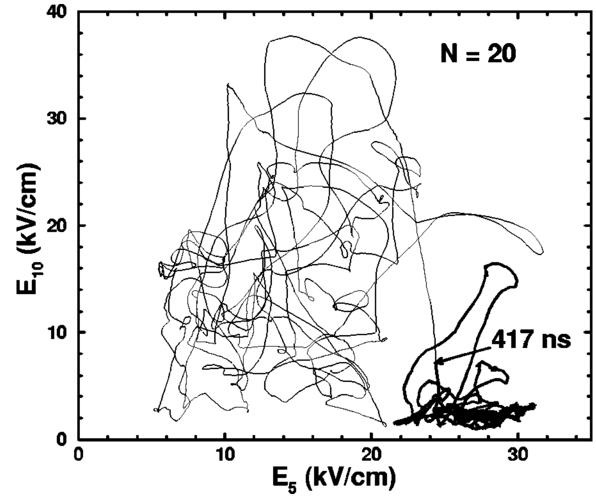

FIG. 6. The same as in Fig. 5 but for fifth and tenth barriers.

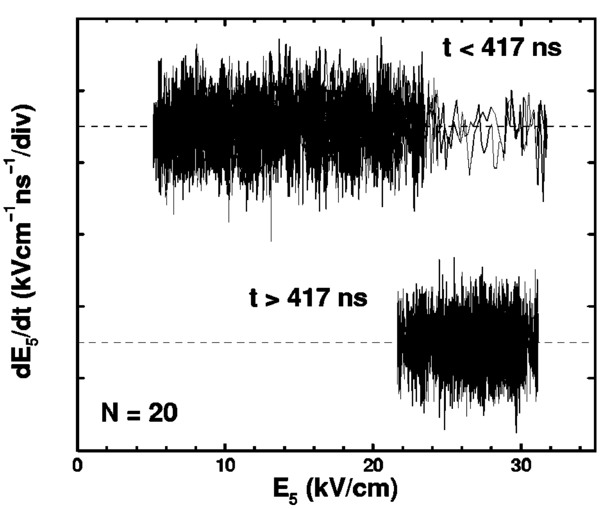

FIG. 7. Phase portraits of the electric field in fifth barrier in the structures with 20 QW's before and after the transition.

IV. CONCLUSION

In summary, we studied nonlinear nonequilibrium processes in multiple QW structures with uncoupled QW's under the influence of infrared radiation using the Monte Carlo simulation technique. It was shown that spatially periodic (or near periodic) electric-field domains with the period coinciding with double the period of the QW structure, can occur in the structures with a different number of QWs. The features of the dynamics of electric-field distributions and the occurrence of spatially periodic electric-field domains is attributed to the instability of waves associated with the recharging of QW's. The formed periodic domains exhibit aperiodic oscillations of their amplitude. As a fast formation of periodic domains in the structures with odd numbers of QW's is a direct consequence of the development of recharging instability and it takes the time commensurable with the characteristic recharging times, the formation of similar domains in the structures with even numbers of QW's can pass through a long stage of strong spatiotemporal oscillations. The predicted effects can substantially influence the performance of QWIP's and other infrared devices based on QW structures.

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[1] B.F. Levine, J. Appl. Phys. **74**, R1 (1993).

[2] R. Tsu and L. Esaki, Appl. Phys. Lett. **19**, 246 (1971).

[3] R.F. Kazarinov and R.A. Suris, Fiz. Tech. Poluprov. **6**, 148 (1972) [Sov. Phys. Semicond. **6**, 120 (1972)].

[4] R.A. Suris, Fiz. Tech. Poluprov. **7**, 1540 (1973) [Sov. Phys. Semicond. **7**, 1030 (1974)].

[5] K.K. Choi, B.F. Levine, R.J. Malik, J. Walker, and C.G. Bethea, Phys. Rev. B **35**, 4172 (1987).

[6] S.H. Kwok, H.G. Grahn, M. Ramsteiner, K. Ploog, F. Prengel, A. Wacker, E. Schoöll, S. Murugar, and R. Merlin, Phys. Rev. B **51**, 9943 (1995).

[7] O.M. Bulashenko and L.L. Bonilla, Phys. Rev. B **52**, 7849 (1995).

[8] A. Wacker, M. Moscoso, M. Kindelan, and L.L. Bonilla, Phys. Rev. B **55**, 2466 (1997).

[9] M. Morifujii and C. Hamaguchi, Phys. Rev. B **58**, 12 842 (1998).

[10] M. Helm, W. Hilber, G. Strasser, R. De Meester, F.M. Peeters, and A. Wacker, Phys. Rev. Lett. **82**, 3120 (1999).

[11] A.A. Ignatov and A.-P. Jauho, J. Appl. Phys. **85**, 3643 (1999).

[12] S.R. Andrews and B.A. Miller, J. Appl. Phys. **70**, 993 (1991).

[13] H.C. Liu, Appl. Phys. Lett. **60**, 1507 (1992).

[14] E. Rosencher, B. Vinter, F. Luc, L. Thibaudeau, P. Bois, and J. Nagle, IEEE Trans. Quantum Electron. **30**, 2875 (1994).

[15] M. Ershov, V. Ryzhii, and C. Hamaguchi, Appl. Phys. Lett. **67**, 3147 (1995).

[16] V.D. Shadrin, V.V. Mitin, V.A. Kochelap, and K.K. Choi, J. Appl. Phys. **77**, 1771 (1995).

[17] L. Thibaudeau, P. Bois, and J.Y. Duboz, J. Appl. Phys. **79**, 446 (1996).

[18] V. Ryzhii, J. Appl. Phys. **81**, 6442 (1997).

[19] N. Schneider, C. Melmelstein, R. Rehm, C. Schönbein, A. Sa'ar, and M. Walther, Phys. Rev. B **57**, R15 096 (1998).

[20] A. Sa'ar, C. Mermelstein, H. Schneider, C. Schoenbein, and M. Walther, IEEE Photonics Technol. Lett. **10**, 1470 (1998).

[21] V. Ryzhii and H.C. Liu, Jpn. J. Appl. Phys. **38**, 5815 (1999).

[22] V. Ryzhii, I. Khmyrova, and M. Ryzhii, Jpn. J. Appl. Phys. **36**, 2596 (1997).

[23] M. Ryzhii and V. Ryzhii, Appl. Phys. Lett. **72**, 842 (1997).

[24] M. Ryzhii, V. Ryzhii, and M. Willander, J. Appl. Phys. **84**, 3403 (1998).

[25] M. Ryzhii and V. Ryzhii, Jpn. J. Appl. Phys. **38**, 5922 (1999).

[26] M. Ryzhii, V. Ryzhii, R. Suris, and C. Hamaguchi, Jpn. J. Appl. Phys., Part 2 **38**, L1388 (1999).

[27] M. Ryzhii, V. Ryzhii, R. Suris, and C. Hamaguchi, Phys. Rev. B **61**, 2742 (2000).

[28] R.F. Kazarinov, R.A. Suris, and B.I. Fuks, Fiz. Tech. Poluprovedn. **7**, 149 (1973) [Sov. Phys. Semicond. **7**, 102 (1973)].

[29] R.A. Suris and B.I. Fuks, Fiz. Tech. Poluprovedn. **7**, 1556 (1973) [Sov. Phys. Semicond. **7**, 1039 (1974)].

[30] I. Khmyrova, M. Ryzhii, V. Ryzhii, R. Suris, and C. Hamaguchi, Jpn. J. Appl. Phys. **38**, 6654 (1999).

[31] J.A. Brum and G. Bastard, Phys. Rev. B **33**, 1420 (1986).

[32] D. Morris, D. Deveaud, A. Regreny, and P. Auvray, Phys. Rev. B **47**, 6819 (1993).

[33] L.F. Register and K. Hess, Appl. Phys. Lett. **71**, 1222 (1997).

[34] A. Zakharova and V. Ryzhii, Fiz. Tech. Poluprovedn. **25**, 402 (1991) [Sov. Phys. Semicond. **25**, 244 (1991)].

[35] J. Peinke, J. Parisi, O. E. Rössler, and R. Stoop, *Encounter with Chaos* (Springer-Verlag, Berlin, 1992).

[36] E. Ott, *Chaos in Dynamical Systems* (Cambridge University Press, Cambridge, 1993).