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Semiconductor Cells with N-Type Photocurrent–Voltage Characteristic

A New Class of Nonlinear Optical Elements

By

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Electrooptic effects are shown to result in an N-type differential negative resistance of semiconductor cells illuminated with radiation. Various types of optoelectronic elements (bistable element included) are created on the basis of these cells.

Показано, что электрооптические эффекты могут привести к отрицательному дифференциальному сопротивлению N-типа у освещаемого полупроводникового элемента. Различные типы оптоэлектронных устройств (включая бистабильные) были созданы на основе таких элементов.

There are many physical mechanisms which give rise to N-type differential negative resistance in semiconductors. Of special interest is the possibility of obtaining N-type current–voltage characteristics for photocurrent by illumination of semiconductor photosensitive elements due to decreasing absorbed light power in them with increasing applied voltage. On the basis of such electrooptic elements, called self-electrooptic effect devices — SEED, it was possible to make devices for light radiation control. We proposed and created different types of optoelectronic elements with such N-type current–voltage characteristics [1 to 5]. Here we describe them and illustrate the realization of different optoelectronic devices based on such elements.

The principle of obtaining N-type current–voltage characteristics in SEED can be explained in the following way. In any photoelectric device photocurrent is defined by the concentration of nonequilibrium carriers n created by light. This concentration is proportional to the product

$$n \sim \alpha P \,, \tag{1}$$

where α is the absorption coefficient of the SEED material and P the light power inside the SEED. N-type current–voltage characteristics may take place if any of the values α or P decrease with growing voltage applied to the SEED (U). Increase of this voltage (U), that is electric field (E) inside the SEED, can alter the refractive index and the absorption coefficient of the SEED material. The small change in the refractive index may not produce essential changes in the light power in ordinary samples. However situation is radically different when our sample has Fabry-Perot resonator shape. In this case a small increase or decrease of the refraction index due to increasing electric field (E) may cause such a change of optical length between the mirrors of the Fabry-Perot resonator sufficient oscillations of light power inside the SEED. In connection with (1) the reduction of light power by these oscillations gives rise to a

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decrease of the concentration of nonequilibrium carriers and accordingly to an N-type current voltage characteristics [1, 2, 4].

We investigated the current–voltage characteristics of a photoresistor made as a Fabry-Perot resonator illuminated with laser radiation of $\lambda = 1.15$ µm wavelength. The photoresistor was made of semiinsulating GaAs(Cr) and the photocurrent created by illumination appeared due to impurity phototransitions. Fig. 1 shows that the current–voltage characteristics of the photoresistor has wave form with regions of negative differential resistance. This form of the current–voltage characteristics can be explained qualitatively as follows. An increase in the voltage heats the sample when the photocurrent flows through it. An increase in the photoresistor temperature alters the refractive index n'. The change in the refracitve index, i.e. the change in the optical length, causes oscillations of the radiation power in the sample and alters the photocurrent.

In our following experiments we studied the current–voltage characteristics of a reverse-biased photodiode in the form of a Fabry-Perot resonator illuminated with

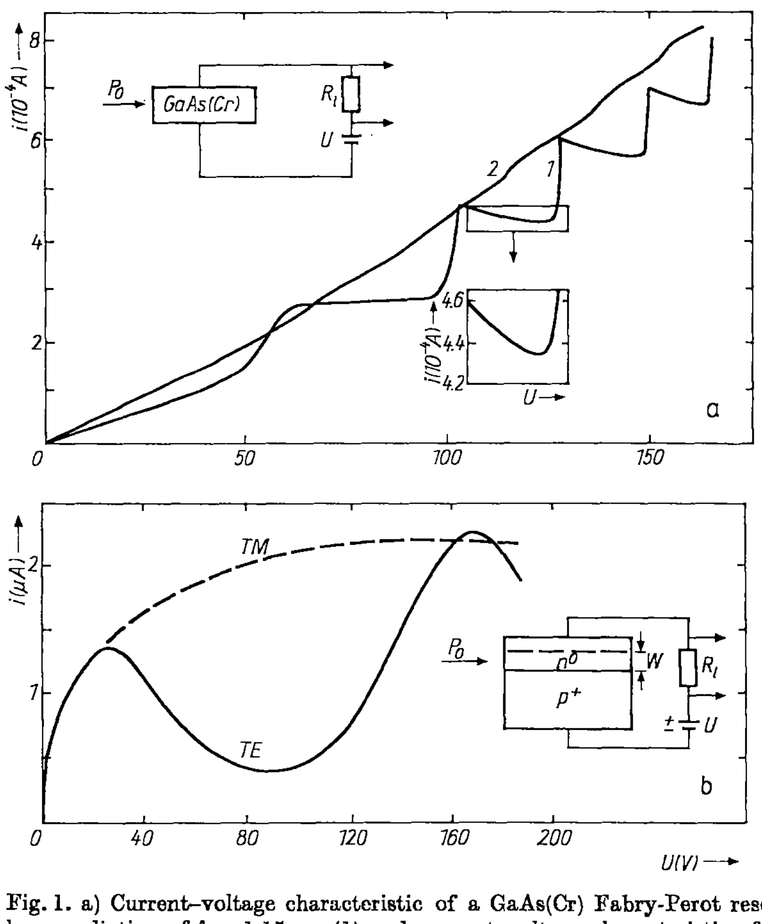

Fig. 1. a) Current–voltage characteristic of a GaAs(Cr) Fabry-Perot resonator illuminated with laser radiation of $\lambda = 1.15$ µm (1) and current–voltage characteristic of a corresponding photoresistor with one of the resonator mirrors deliberately damaged (2). b) Current-voltage characteristics of a reverse-biased photodiode in the form a Fabry-Perot resonator obtained for two different polarizations of $\lambda = 1.15$ µm laser radiation

$\lambda = 1.15\ \mu m$ laser radiation (see Fig. 1). The photocurrent in the space charge region W was generated due to two-stage optical transitions via accidental, deep impurity centres. The current–voltage characteristics of the photodiode were determined for radiation of TE and TM polarizations. The growth in the reverse bias increased the electric field E in the space charge region of the photodiode. The increase in electric field resulted in a change in the refractive index for the radiation with TE polarization due to the electrooptic effect. The power of the TE-polarized radiation in the space charge region varied periodically as the bias voltage increased, which determined the shape of the current–voltage characteristics.

Let us now discuss the possibility of obtaining N-type negative resistance due to electroabsorption effects. There are two situations. The increasing electric field in the semiconductor results in an increase of absorption coefficient, if the photon energy is less than the energy gap, and may result in a decrease of absorption coefficient, if the photon energy exceeds slightly the energy gap. The first case is known as the Franz-Keldysh effect. This effect cannot give rise to N-type negative resistance in a semiconductor photocell, and, on the contrary, it may result only in a sharp rise of photocurrent when the applied voltage is increased. Exactly this situation takes place if we work with an ordinary semiconductor photodiode. However, the situation is radically different when our sample has the Fabry-Perot resonator shape. In this case the power absorbed in the resonator in the resonance region may decrease on increasing the absorption coefficient as the applied voltage increases. This may occur because in the resonance region the increase in the absorption coefficient α may result in a drastic drop in the radiation power inside the resonator P, so that in the product αP this reduction overcompensates the rise of the absorption coefficient itself. Calculated curves in Fig. 2 (see [4]) show the power absorbed in the resonator photocell, or the photocurrent proportional to it, as a function of the product of absorption coefficient and the distance between the resonator mirrors. The dashed curves show the same relations with the resonator absent. Thus the current–voltage characteristics of the resonator photocell must have a falling section due to the Franz-Keldysh effect [3]. This was understood alread 1981, but only now we are carrying out experiments for observing this effect. Let us now consider the other situation, when the photon energy exceeds slightly the energy gap of the semiconductor. In this case the electroabsorption coefficient of the semiconductor may decrease as the electric field increases. Such a dependence following from the one-electron theory of electroabsorption, has been long known and has been verified in experiments on radiation transmission [11].

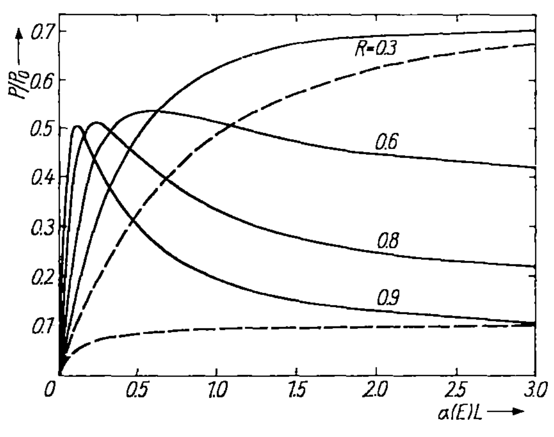

Fig. 2. The power absorbed in the resonator in the resonance region as a function of the product of absorption coefficient and the distance between the resonator mirrors. The dashed curves show the same relations without the resonator. R is the reflection coefficient of the resonator mirrors

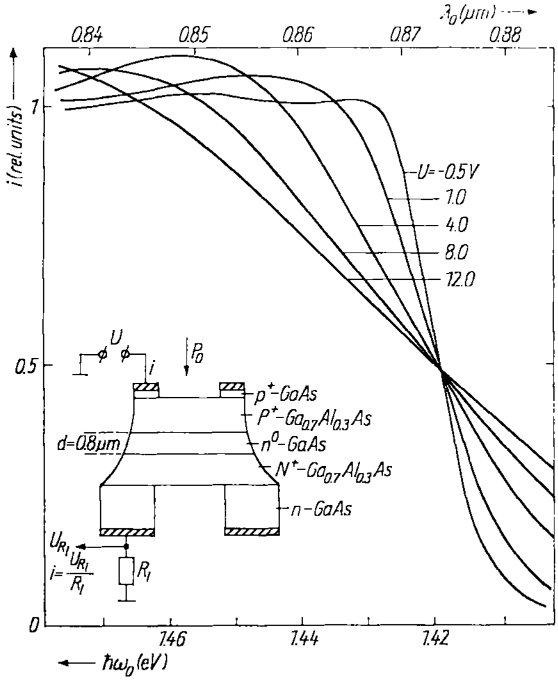

Fig. 3. Dependence of the photocurrent on the photon energy of the radiation used to illuminate the structure subjected to various reverse bias voltage U (— forward bias, + reverse bias). Inset: Schematic representation of the investigated structure. The spectral half-width of the investigated radiation was $\Delta\lambda \approx 2$ nm. $Eg_{GaAs} \approx 1.42$ eV. Light power (P_0) decreases smoothly by 15 % as λ_0 changes from 0.88 μm to 0.84 μm

Reduction of absorption coefficient with electric field in the narrow-gap i-type layer of a double p–i–n heterostructure enables us to obtain N-type current–voltage characteristics in a simple and elegant way [4, 5, 9]. We investigated the spectral dependence of the photocurrent of a p–i–n heterostructure with different voltages applied. The structure was grown by metallorganic hydride gas epitaxy. Its parameters are shown in Fig. 3. The experimental dependences show that there is a wide spectral region in which the photocurrent in the structure decreases with increasing

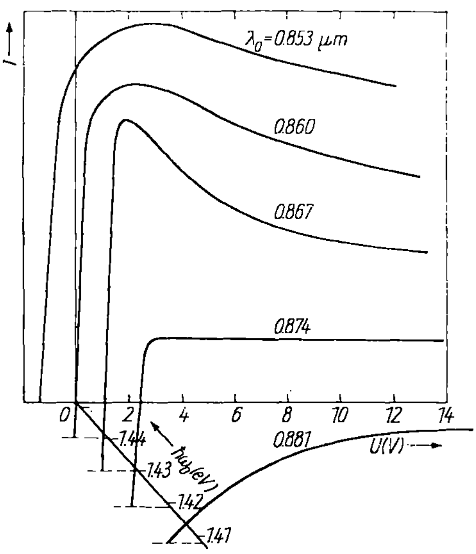

Fig. 4. Current–voltage characteristics of a double p–i–n heterostructure for different photon energies

electric field in the i-layer. In Fig. 4 experimental current–voltage characteristics are shown for radiation of different photon energy. Fig. 5 shows the experimental current–voltage characteristics of our p–i–n heterostructure [5] and the characteristics of the p–i–n heterostructure with quantum wells in the intrinsic region of the structure [6]. In the latter case the characteristics is N-shaped under electroabsorption conditions because of a reduction in the electroabsorption coefficient α, but in this case this happens at photon energies corresponding to an exciton resonance of MQW structures with increasing electric field E, which can be explained by a new mechanism which is known as the quantum-confirmed Stark effect [7]. It is clear from this figure that the characteristics are similar in these two cases.

It was shown that there are different experimental situations in which electrooptic effects allow to obtain N-type current–voltage characteristics. The presence of such characteristics permits to realize optical bistability in the structure [2 to 4]. To obtain it it is necessary to take such load resistance that the load line can intersect the current–voltage characteristics in three points. Fig. 6 shows an experimental bistable characteristics obtained on our double p–i–n heterostructure. In this case the SEED has no resonator and nonmonochromatic radiation can be used. If we remove the absorbing substrate we can obtain optical bistability in transmission. These experiments are under way now.

N-type current–voltage characteristics allow to obtain self-modulation of photocurrent and radiation transmitted through the structure [8, 6]. There is the following very interesting circumstance: A section of differential negative resistance of our resonator-free SEED stretches into the region of forward bias voltages. So there is in

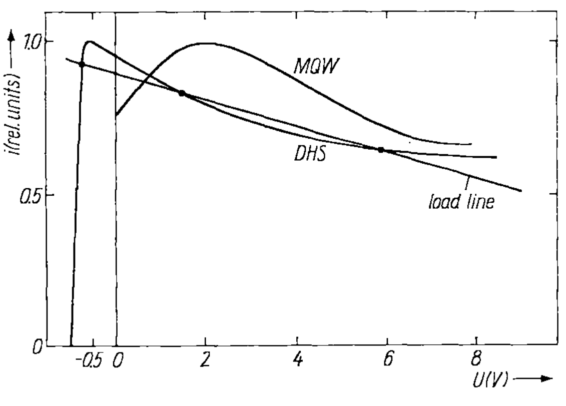

Fig. 5

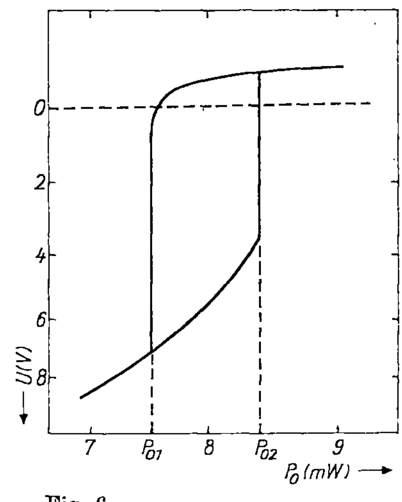

Fig. 6

Fig. 5. Current–voltage characteristics of a double heterostructure (DHS) [5] and a multiple quantum well (MQW) p–i–n heterostructure [6]. In the case of double heterostructures the photon energy $\hbar\omega_0 = 1.4335$ eV exceeds slightly the energy gap of the i-layer, whereas in the case of the MQW heterostructure the photon energy ($\hbar\omega_0 = 1.4559$ eV) corresponds to exciton resonance of the i-layer of this structure [6]. The spectral half-width of the radiation line was $\Delta\lambda \approx 5$ nm for DHS

Fig. 6. Experimental bistable characteristic for photovoltage obtained on a double p–i–n heterostructure. Switching time $\tau_{off} = R_1C \approx 5 \times 10^{-8}$ s

principle a possibility to obtain self-modulation of photocurrent and radiation transmitted through the structure when it works in the barrier regime. Fig. 7 shows experimental current–voltage characteristics of our SEED at illumination with ordinary semiconductor laser radiation. Current–voltage characteristics had sections of differential negative resistance stretching into the region of forward bias voltages. The arrangement shown in Fig. 7 is used to produce undamped oscillations in the circuit containing an N-type negative resistance. We choose the resistance R_l so that the load line intersects some current–voltage characteristics on the falling sections. Undamped oscillations are produced if

$$L > |R^-|\, RC = |R^-|\, (R_l + R_L + R_S)\, C \tag{2}$$

is satisfied, where L is the inductance, $|R^-| = \mathrm{d}V/\mathrm{d}i$ the absolute value of the negative differential resistance near point A, R_l the load resistance, R_L the active resistance of the inductance, R_s the series resistance of the SEED, and C the capacitance of the SEED. From Fig. 7 one can see that the absolute value of the differential negative resistance $|R^-|$ near the points of intersection of load line and current–voltage characteristics A changes as the light power increases. If the light power is low, the absolute value of this differential negative resistance is high and no oscillations are recorded. As the light power increases, condition (2) is satisfied and sine oscillations appear (Fig. 8). When we further increase the light power the oscillation amplitude increases and the shape gets distorted. As the light power continues to grow when the load line intersects the current–voltage characteristics near its maximum, the absolute value of the differential negative resistance begins increasing and the oscillations vanish. Fig. 8 shows that oscillations exist only in a confined region of light power, the rise and disappearance of oscillations occurring very sharply while light power changes smoothly. Using SEED with a smaller area ($C \approx 10$ pF), and reducing the resistance R to $\approx 50\ \Omega$ ($R_l = 0$), it is possible to satisfy condition (2) with $|R^-| \approx 10^4\ \Omega$

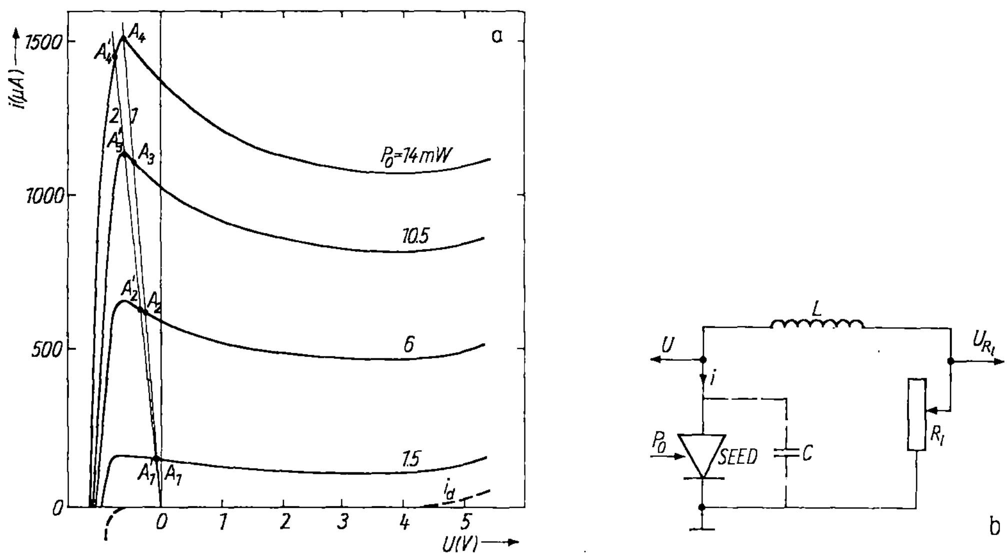

Fig. 7. a) Experimental current–voltage characteristics of our resonator-free SEED illuminated with ordinary semiconductor laser radiation; i_d is the dark current. (1) $R_l = 500$ and (2) 600 Ω (active layer width $d = 0.25$ μm). b) Experimental layout for obtaining undamped oscillationsin the circuit containing SEED with an N-type negative resistance ($L = 0.05$ M, $C \approx 300$ pF)

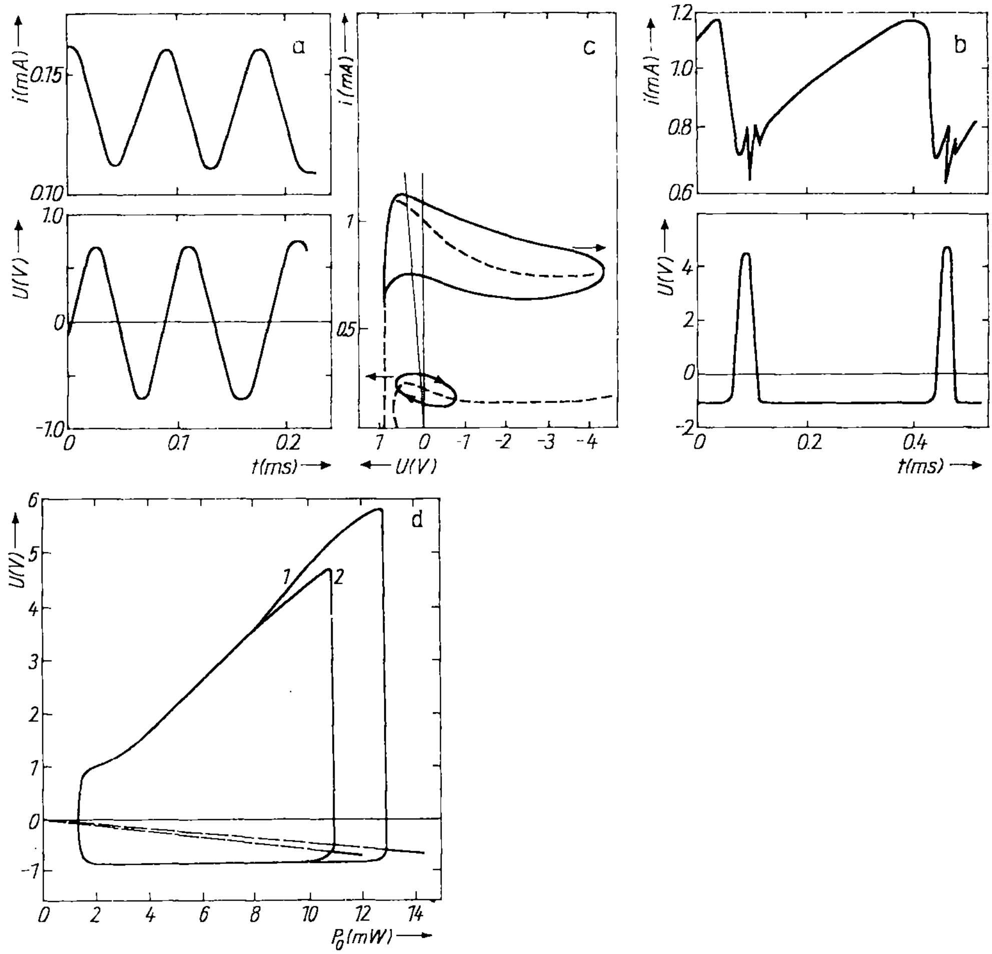

Fig. 8. a), b) Oscilloscope traces of the oscillations of photocurrent and photovoltage across the resonator-free SEED. c) Oscilloscope traces of cycles of current–voltage oscillations of the SEED corresponding to a) and b). The dashed curves are the photocurrent–voltage characteristics. d) Amplitude of the ac photovoltage across the SEED vs. the light power incident on the SEED, P_0, for various values of R_l ((1) $R_l = 500$ and (2) 600 Ω)

($P_0 \approx 12$ mW) and $L \approx 10^{-5}$ H. Near the threshold for the appearance of the oscillations (at $P_0 \approx 12$ mW) we found sinusoidal oscillations of the photovoltage, with a frequency $f \approx 20$ MHz, across the SEED. It is obvious that this resonator-free SEED can also work in the univibration regime [10] and thus become basis for all-optical logical elements.

In conclusion, I should like to emphasize that the switching energy of our resonator-free SEED is $\approx 10^{-14}$ J/μ^2. In my opinion, if we make the SEED capacitance small we will be able to obtain switching times $\approx 10^{-11}$ s.

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References

[1] B. S. Ryvkin, Soviet. Phys. — J. tech. Phys. Letters **5**, 25 (1979).
[2] B. S. Ryvkin and M. N. Stepanova, Soviet. Phys. — J. tech. Phys. Letters **8**, 413 (1982).
[3] B. S. Ryvkin, Soviet. Phys. — Semicond. **15**, 796 (1981).
[4] B. S. Ryvkin, Proc. All-Union Conf. Physics of Semiconductors, Baku **1**, 56 (1982) (in Russian); Soviet. Phys. — Semicond. **19**, 1 (1985).
[5] S. N. Aleksandrov, M. G. Ivanov, M. I. Nemenov, B. S. Ryvkin, M. A. Sinitsyn, and B. S. Yavich, Soviet Phys. — Semicond. **21**, 430 (1987).
[6] D. A. B. Miller, D. S. Chemla, T. C. Damen, A. G. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, Appl. Phys. Letters **45**, 13 (1984); IEEE J. Quantum. Electron. **21**, 1462 (1985).
[7] D. A. B. Miller, D. S. Chemla, T. C. Damen, A. G. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, Phys. Rev. B **32**, 1043 (1985).
[8] B. S. Ryvkin, Soviet. Phys. — J. tech. Phys. Letters **5**, 239 (1979).
[9] D. M. Butusov, G. G. Gotsadze, V. R. Larionov, and B. S. Ryvkin, Soviet Phys. — J. tech. Phys. Letters **13**, 338 (1987).
[10] D. M. Butusov, G. G. Gotsadze, V. R. Larionov, and B. S. Ryvkin, Soviet Phys. — J. tech. Phys. Letters **13**, 12 (1987).
[11] J. I. Pankove, Optical Processes in Semiconductors, Prentice-Hall, Inc., Englewood Cliffs (N.J.) (1971).

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