Spin Gunn Effect

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We predict that the flow of unpolarized current in electron-doped GaAs and InP at room temperature is unstable at high electric fields to the dynamic formation of spin-polarized current pulses. Spin-polarized current is spontaneously generated because the conductivity of a spin-polarized electron gas differs from that of an unpolarized electron gas, even in the absence of spin-orbit interaction. Magnetic fields are not required for the generation of these spin-polarized current pulses, although they can help align the polarization of sequential pulses along the same axis.

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Spin-based semiconductor electronics ("spintronics") requires the generation of spin polarization in nonmagnetic semiconductors [1,2]. Approaches through the injection of spin-polarized electrons or holes from magnetic materials [3–7], and spin-filtered [8,9] or spin-selective [10–14] currents using the spin-orbit interaction have been considered. These rely on an energetic difference between spin-up and spin-down carriers in the some element of a circuit. Here we identify a different approach.

We show that initially unpolarized electron current flow in semiconductors can be unstable towards the spontaneous formation of spin-polarized current pulses even without an applied magnetic field. The mechanism we propose is related to the charge Gunn effect [15], in which homogeneous charge current flow is unstable to the spontaneous formation of high-electric-field domains, inhomogeneous charge distributions, and current pulses. We predict the "spin Gunn effect" can be seen at room temperature in GaAs and InP, and possibly [16] GaN. The dependence of the electron drift velocity on spin polarization—from the Pauli exclusion principle—drives the spin Gunn effect. A room-temperature source of spin-polarized electrons from a nonmagnetic semiconductor would significantly advance spintronic devices. The high-frequency oscillatory nature of these pulses suggests new possibilities, such as may emerge from matching the oscillation frequency of a spin-polarized source to the precession frequency of spins in another material.

We consider a material in which a charge Gunn domain [15] has formed in the ordinary way. Thermal fluctuations lead to a small, randomly oriented spin polarization $P = (n_\uparrow - n_\downarrow)/n$, where $n_\uparrow(n_\downarrow)$ is the density of spin-up (spin-down) electrons and $n = n_\uparrow + n_\downarrow$. At room temperature a $P \sim 0.01\%$ in a small (1 μm^3) region of GaAs doped to an electron density of 10^{18} cm^{-3} costs k_BT to excite, where k_B is the Boltzmann constant and T the temperature. The application of an external magnetic field would preferentially orient these fluctuations antiparallel to the field (the g factor for GaAs is -0.44 so a magnetic field of 0.2 T would polarize spins $\sim$0.01%; a field of 0.5 T would dominate over thermal fluctuations in a 1 μm^3 region). Spin-orbit effects [17] could also seed the initial oriented spin polarization. Once $P \neq 0$, the amplifying effect described in this Letter causes it to grow until it reaches a saturation limit which can be near unity.

The amplification of this small initial spin polarization originates from an electron velocity ($v = \mu E$, where μ is the mobility and E the electric field) that (1) depends on the local spin polarization of the electrons, and (2) differs for spin-up and spin-down electrons. The mobility depends on the carrier density, and thus the mobility for spin-up carriers, $\mu_\uparrow = \mu(n_\uparrow)$, differs from that for spin-down carriers, $\mu_\downarrow = \mu(n_\downarrow)$. The mobility near $P = 0$ can be approximated as

$$\mu_{\uparrow(\downarrow)} = \mu(n/2)(1 + (-)\alpha P), \tag{1}$$

where

$$\alpha = \lim_{P\to 0} \frac{\mu_\uparrow - \mu_\downarrow}{2P\mu_{\rm av}} = \lim_{P\to 0} \frac{\mu(n_\uparrow) - \mu(n_\downarrow)}{2P\mu_{\rm av}}, \tag{2}$$

and $\mu_{\rm av} = (n_\uparrow\mu_\uparrow + n_\downarrow\mu_\downarrow)/n$ is the average mobility. For a bulk parabolic band with effective mass m^*,

$$\mu_{\uparrow(\downarrow)} = \frac{e}{m^*} \frac{\int_0^\infty \epsilon^{3/2}\tau(\epsilon)(\partial f_{\uparrow(\downarrow)}(\epsilon)/\partial\epsilon)d\epsilon}{\int_0^\infty \epsilon^{3/2}(\partial f_{\uparrow(\downarrow)}(\epsilon)/\partial\epsilon)d\epsilon}, \tag{3}$$

where $f_{\uparrow(\downarrow)}(\epsilon)$ is the Fermi occupation function at energy ϵ of spin $\uparrow$ ($\downarrow$), $\tau(\epsilon)$ is the carrier scattering time, and e is the electron's charge [18]. The dominant *spin-conserving* electron scattering mechanism, which determines $\tau(\epsilon)$ (tabulated in Ref. [18] for common mechanisms), determines the value of α we calculate below.

Most semiconductors have $\alpha \neq 0$. As shown in Fig. 1, due to the Pauli exclusion principle the chemical potentials of spin-up and spin-down electrons [$f_\uparrow(\epsilon)$ and $f_\downarrow(\epsilon)$] in a spin-polarized electron gas are different. Thus in a polarized degenerate electron gas the energy distributions of spin-up and spin-down electrons differ, and the mobilities from Eq. (3) for $P \neq 0$ will differ from those for $P = 0$. For scattering of conduction electrons from ionized impurities, acoustic phonons via piezoelectric coupling, or longitudinal phonons via Fröhlich coupling (LO-phonon

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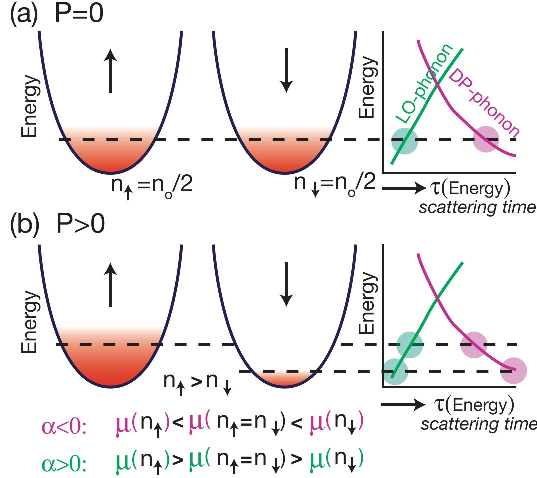

FIG. 1 (color). Scattering of spin-up and spin-down electrons. (a) The electrons are unpolarized, and the mobility of spin-up and spin-down electrons is identical. (b) The electrons are spin polarized, and the mobility of spin-up electrons is either smaller ($\alpha < 0$, see purple curve) or larger ($\alpha > 0$, see green curve) than the mobility of spin-down electrons.

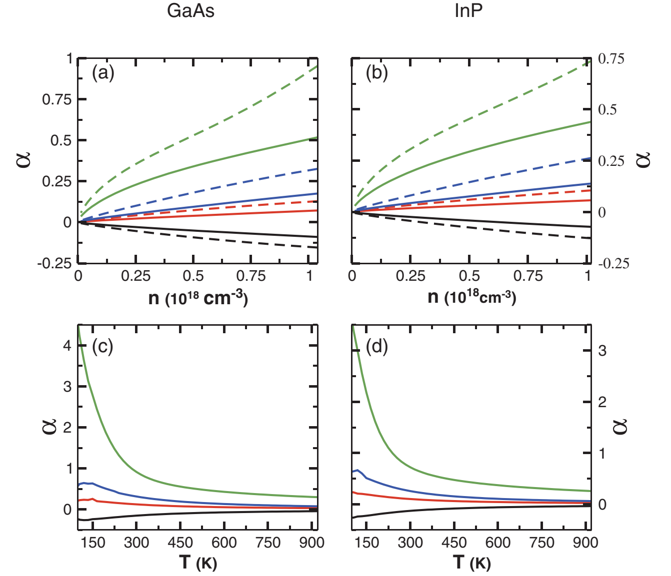

FIG. 2 (color). (a),(b) $\alpha(n)$ for GaAs and InP at 300 K (dashed line) and 500 K (solid line). (c),(d) $\alpha(T)$ for GaAs and InP for $n = 10^{18}$ cm^{-3}. Green curves are LO-phonon scattering, blue curves are ionized impurity scattering, red curves are piezoelectric-phonon scattering, and black curves are DP-phonon scattering.

scattering), the low-energy electrons are scattered more than the high-energy electrons [18], as shown in Fig. 1. In the spin-polarized electron gas the increased energy of the spin-up electrons leads to longer scattering times and thus a higher mobility than for spin-down electrons. This situation corresponds to $\alpha > 0$ in Eq. (1). If the dominant scattering process involves acoustic phonons coupling via the deformation potential (DP-phonon scattering), then the spin-up electrons scatter more than the spin-down electrons [18], as also shown in Fig. 1, and $\alpha < 0$. The only common scattering process that produces $\alpha = 0$ is neutral-impurity scattering. Thus the mobility of electrons for $P \neq 0$ almost always depends strongly on the spin orientation, even when there is no explicit spin dependence in the scattering processes themselves. The spin-polarization dependence of the mobility originates from the same energy dependence of carrier scattering that produces a density-dependent mobility $\mu(n)$ [18], and thus should be generic.

Calculations for GaAs and InP for α from Eqs. (2) and (3), as a function of density at 300 and 500 K, and as a function of temperature for $n = 10^{18}$ cm^{-3}, are shown in Fig. 2. For these processes $|\alpha|$ increases with increasing n, and decreases as T increases, with $|\alpha| > 0.1$ for $T < 500$ K at $n = 10^{18}$ cm^{-3}. At and above room temperature, LO-phonon scattering dominates and $\alpha > 0$.

Electron-electron interactions produce a frictional interaction between differently moving spin-up and spin-down electrons. This "spin drag" [19] can be accounted for by replacing α with $\alpha[1 - (2\rho_{\uparrow\downarrow}/\rho_{\uparrow\uparrow})]$, where $\rho_{\uparrow\downarrow}$ is the spin transresistivity and $\rho_{\uparrow\uparrow}$ is the ordinary resistivity of spin-up electrons. Calculations of the spin transresistivity in Ref. [19] provide an estimate of $(2\rho_{\uparrow\downarrow}/\rho_{\uparrow\uparrow}) = 0.002$ for $T = 500$ K and $n = 10^{18}$ cm^{-3}, and justify neglecting spin drag effects in our calculations.

We now consider the effect of $\alpha \neq 0$ on the spin polarization of electrons in an initially unpolarized charge Gunn domain. The Gunn domain itself moves in a self-sustaining way—an inhomogeneous electric field moves the charge, and the shifting space-charge region moves the electric field—and the net result is the collective motion of the electric field shape and the space-charge region through the sample. A small difference in mobility between spin-up and spin-down electrons means fewer electrons of one spin species will flow in response to these electric fields. This increase of P further enhances $\mu_\uparrow - \mu_\downarrow$ (positive feedback), which drives a further increase in P. The electric field is determined by the charge density through the Poisson equation (independent of P), so the domain continues to move as before but now with $P \neq 0$.

The very short (< 100 fs) electron momentum scattering time permits use of drift-diffusion equations [1] to calculate the time dependence of the spin polarization,

$$\frac{\partial n_\uparrow}{\partial t} = -\frac{n_\uparrow - n_\downarrow}{2T_1} - \frac{\partial(n_\uparrow v_\uparrow)}{\partial x} + D_\uparrow \frac{\partial^2 n_\uparrow}{\partial x^2}, \tag{4}$$

$$\frac{\partial n_\downarrow}{\partial t} = -\frac{n_\downarrow - n_\uparrow}{2T_1} - \frac{\partial(n_\downarrow v_\downarrow)}{\partial x} + D_\downarrow \frac{\partial^2 n_\downarrow}{\partial x^2}, \tag{5}$$

where T_1 is the spin relaxation time of the electrons and $D_\uparrow$ and $D_\downarrow$ are the diffusion constants for spin-up and spin-down electrons, respectively. Using Eqs. (1)–(5), keeping only terms up to first order in P, neglecting pure diffusion effects, and shifting to the domain's frame ($x' = x - v_{\rm dom}t$, where $v_{\rm dom}$ is the domain's velocity),

$$\frac{\partial P}{\partial t} = -\frac{\alpha}{n}\frac{\partial[nE\mu]}{\partial x'}P - \frac{P}{T_1} + [\mu(1-\alpha)E - v_{\rm dom}]\frac{\partial P}{\partial x'} \sim \left(\gamma - \frac{1}{T_1}\right)P. \qquad (6)$$

This equation predicts spin amplification if $\gamma > T_1^{-1}$. The $\partial P/\partial x'$ term describes the flow of inhomogeneous spin polarization within the domain; similar terms describing charge flow are ignored in treating the charge Gunn effect itself [20], as they do not change any qualitative behavior. Our treatment here neglects this term, which we estimate to be over an order of magnitude smaller than γP.

The first observation about Eq. (6) is that the central quantity γ is proportional to the spatial variation of the *drift* current. $\partial n_s/\partial t = \nabla \cdot \mathbf{j}_s$, where $\mathbf{j}_s$ is the current of carriers with spin s, so differing spin-up and spin-down currents (from $\mu_\uparrow \neq \mu_\downarrow$) produce differing spin-up and spin-down density accumulation. γ is largest for situations involving large charge imbalances (yet still less than the material's breakdown field). High doping levels produce more localized domains and less microwave power in the fundamental oscillation mode, so ordinary doping levels are in the range of 10^{14}–10^{16} cm^{-3} for charge Gunn devices. For the spin Gunn effect, however, a higher density leads to larger P.

We now quantitatively calculate the value of γ for a doping level of 10^{18} cm^{-3} at a 300 K lattice temperature in GaAs and InP. We ignore higher-order effects and evaluate $-(\alpha/n)\partial[nE\mu(n/2)]/\partial x'$ for $P = 0$. Hence

$$\gamma = -\alpha\mu E\left[\frac{e(n-n_0)}{\epsilon_s E} + \frac{1}{n}\frac{\partial n}{\partial x'} + \frac{1}{\mu}\frac{\partial \mu}{\partial x'}\right], \qquad (7)$$

where ϵ_s is the dielectric permittivity of the semiconductor. Our calculation of $n(x')$ and $E(x')$ for the Gunn domain follows that of Sze [21] for a mature, steady-state domain. We assume the electrons in the lower valley and the upper valleys have the same temperature [22,23] and that the diffusion constant is independent of the electric field, the electron density, and spin. The time-dependent electron current is equal to the displacement current,

$$J = env(E) - eD\frac{\partial n}{\partial x} = -\epsilon_s\frac{\partial E}{\partial t}. \qquad (8)$$

For a high-field domain propagating without a change of shape, in the domain's reference frame

$$\frac{eD}{\epsilon_s}\frac{dn}{dE} = \frac{\{n[v(E) - v_{\rm dom}] - n_0(v_R - v_{\rm dom})\}}{n - n_0}. \qquad (9)$$

The electron drift velocity outside of the domain, $v_R = J/(en_0)$, and the electric field at such points is E_R. The solution of Eq. (9) is

$$\frac{n}{n_0} - \ln\left(\frac{n}{n_0}\right) - 1 = \frac{\epsilon_s}{en_0 D}\int_{E_R}^{E}\left\{[v(E') - {\rm v}_{\rm dom}] - \frac{n}{n_0}(v_R - v_{\rm dom})\right\}dE'. \qquad (10)$$

A self-consistent solution to Eq. (10) determines $E(n)$. $E(x')$ can then be found from Poisson's equation,

$$x' = x'_0 + \frac{\epsilon_s}{e}\int_{E_{\rm dom}}^{E}\frac{dE}{n - n_0}, \qquad (11)$$

where x'_0 is the location of the peak electric field in the domain's frame. The local electron temperature T_e is

$$k_B T_e = k_B T_l + (2/3)e\tau_\epsilon \mu E^2[1 + R\exp(-\Delta E/k_B T_e)]^{-1}, \qquad (12)$$

where T_l is the lattice temperature, $\tau_\epsilon \sim 10^{-12}$ s the energy relaxation time, ΔE the energy separation between the Γ and L valleys, and R the ratio of the density of states in the L to the Γ valleys (values from Ref. [21]). Figure 3 shows solutions of Eqs. (10) and (11) for n and E as a function of position for GaAs and InP for $T_l = 300$ K.

The spin amplification factor γ is shown in Figs. 3(e) and 3(f) for DP-phonon scattering, and in Figs. 3(g) and 3(h) for LO-phonon scattering. As T_e varies with position according to Eq. (12), α must be evaluated as a function of T_e and n to determine γ properly. The electric field, and

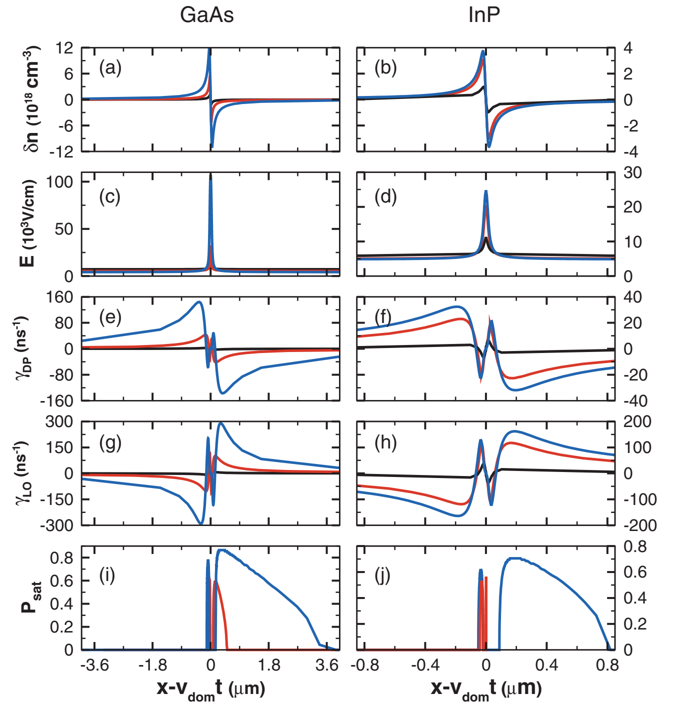

FIG. 3 (color). Position dependence of the density n [(a) for GaAs, (b) for InP] and the electric field E [(c) for GaAs, (d) for InP] in the domain frame ($x' = 0$ is the domain center). Spin amplification rate γ for DP-phonon scattering [(e) for GaAs, (f) for InP] and for LO-phonon scattering [(g) for GaAs, (h) for InP]. The three curves correspond to different drift velocities far from the domain (different applied voltages to the Gunn diode): black is 5.7×10^6 cm/s for GaAs, 2.6×10^7 cm/s for InP; red is 5.0×10^6 cm/s for GaAs, 2.45×10^7 cm/s for InP; blue is 4.0×10^6 cm/s for GaAs, 2.4×10^7 cm/s for InP. Saturation spin polarization $P_{\rm sat}$ [corresponding to $\gamma(P_{\rm sat}) = T_1^{-1}$] (i) for GaAs and (j) for InP.

thus $\nabla \cdot \mathbf{j}_s$, is largest at the center of the domain. However, T_e is also greatest there, so the largest γ occurs near but not at $x' = 0$. For GaAs there is amplification for $T_1 > 3$ ps, and for InP for $T_1 > 2$ ps.

We propose Gunn diodes with $n \sim 10^{18}$ cm^{-3} for the spin Gunn effect. For a lower doping density of 10^{16} cm^{-3} the T_1 of GaAs at 300 K is 50 ps [24] and our calculated $\gamma \sim 4$ ns^{-1}, so spin amplification is not expected to occur. For $n \sim 10^{18}$ cm^{-3} the T_e at peak $\gamma(x')$ is 500 K, and the T^3 dependence of D'yakonov-Perel' precessional relaxation [24] suggests $T_1 \sim 12$ ps. Our calculated spin amplification rates of $\gamma > 0.4$ ps^{-1} are 5 times larger than this rapid spin relaxation rate, providing confidence that spin amplification will occur for room-temperature devices. At these high temperatures the enhanced electron-electron scattering [25] and the reduced mobility should also increase T_1 far beyond 12 ps. Although higher densities than $n \sim 10^{18}$ cm^{-3} produce even larger γ's, the electric field may exceed breakdown.

The spin Gunn effect is a pulse of highly spin-polarized electrons located just before or just after a charge current pulse, depending on the dominant orbital scattering process. An estimate of the steady-state (saturation) values of the spin polarization ($P_{\rm sat}$) requires an estimate of α for $P \neq 0$. Multiplying the expression in Eq. (2) by $1 - P^2$ yields the proper approximate behavior: amplification near $P = 0$ is unchanged, whereas amplification for $P = \pm 1$ vanishes. Shown in Figs. 3(i) and 3(j) are $P_{\rm sat}$ estimated for LO-phonon scattering determined by setting $T_1 = 10$ ps, using this modified form for $\alpha(P)$, and solving $\gamma(P_{\rm sat}) = T_1^{-1}$. As $\alpha(P = 1) = 0$, α changes 100% between $P = 0$ and $P = 1$. In contrast, n, μ, and E change ~20%. Thus we neglect nonlinear effects on n, μ, and E in our calculation of $P_{\rm sat}$. When $\gamma(P = 0) < T_1^{-1}$, $P_{\rm sat} = 0$. The largest $P_{\rm sat}$ exceeds 80% for both GaAs and InP, and should be directly visible in a Faraday rotation measurement (e.g., Ref. [26]). When there is a convincing electrical method of spin-polarization detection in nonmagnetic semiconductors, these spin-polarized pulses will be detectable in that way.

We have demonstrated that, even when carrier scattering processes are entirely independent of spin, that the carrier mobility depends on the spin polarization of those carriers. This leads to a spin-dependent response of current flow to inhomogeneous electric fields and carrier densities. In the presence of a charge Gunn domain that spin-dependent response generates spin-polarization amplification and spontaneous spin-polarization generation. This spin Gunn effect is robust to temperature and spin relaxation, suggesting a wide range of potential applications and devices. Potential uses of the resulting series of highly spin-polarized pulses (each in register with a charge Gunn domain) include generating a reservoir of spin-polarized carriers within the semiconductor for spin-based logic, modulating the optical properties of semiconductor devices at high speed, and exploring resonant transport through quantum dots. Ultrafast optical excitation of carriers typically involves the repetitive generation of carriers every ~10 ns; our predicted electrically generated pulse trains of spin-polarized current may have similar uses in exploring the spin-dependent physics of various materials, including those with unfavorable optical properties such as silicon.

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[1] *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, N. Samarth, and D. Loss (Springer Verlag, Berlin, 2002).
[2] S. Wolf *et al.*, Science **294**, 1488 (2001).
[3] R. Fiederling *et al.*, Nature (London) **402**, 787 (1999).
[4] Y. Ohno *et al.*, Nature (London) **402**, 790 (1999).
[5] H. J. Zhu *et al.*, Phys. Rev. Lett. **87**, 016601 (2001).
[6] A. T. Hanbicki *et al.*, Appl. Phys. Lett. **80**, 1240 (2002).
[7] A. F. Isakovic *et al.*, Phys. Rev. B **64**, 161304(R) (2001).
[8] Y. Guo *et al.*, J. Appl. Phys. **83**, 4545 (1998).
[9] J. C. Egues, Phys. Rev. Lett. **80**, 4578 (1998).
[10] M. I. D'yakonov and V. I. Perel', Phys. Lett. **35A**, 459 (1971).
[11] L. S. Levitov, Yu. V. Nazarov, and G. M. Éliashberg, Zh. Eksp. Teor. Fiz. **88**, 229 (1985) , [Sov. Phys. JETP **61**, 133 (1985)].
[12] V. M. Edelstein, Solid State Commun. **73**, 233 (1990).
[13] S. Murakami, N. Nagaosa, and S.-C. Zhang, Science **301**, 1348 (2003).
[14] Y. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom, Phys. Rev. Lett. **93**, 176601 (2004).
[15] J. B. Gunn, Solid State Commun. **1**, 88 (1963)
[16] E. Alekseev and D. Pavlidis, Electron. Lett. **36**, 176 (2000); Solid-State Electron. **44**, 941 (2000).
[17] Y. K. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom, Science **306**, 1910 (2004).
[18] For example, M. Cardona and P. Yu, *Fundamentals of Semiconductors* (Springer, New York, 2001), 3rd ed.
[19] I. D'Amico and G. Vignale, Phys. Rev. B **62**, 4853 (2000).
[20] H. Kroemer, in *Topics in Solid State and Quantum Electronics*, edited by W. D. Hershberger (Wiley, New York, 1972).
[21] S. M. Sze, *Physics of Semiconductor Devices* (John Wiley & Sons, New York, 1981), 2nd ed.
[22] C. Hilsum, Proc. IRE **50**, 185 (1962).
[23] D. E. McCumber and A. G. Chynoweth, IEEE Trans. Electron Devices **13**, 4 (1966).
[24] *Optical Orientation*, edited by F. Meier and B. P. Zakharchenya (North-Holland, New York, 1984).
[25] M. M. Glazov and E. L. Ivchenko, JETP Lett. **75**, 403 (2002).
[26] B. Beschoten *et al.*, Phys. Rev. B **63**, 121202(R) (2001).