Spin-polarization autowave in magnetically mixed (semimagnetic) semiconductor

Yu. G. Semenov and V. A. Stefanovich
Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR

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An autowave of the local spin polarization can arise in a semimagnetic semiconductor of the $A^2_{1-x}Mn_xB^6$ type under conditions close to those required for resonator-free optical bistability. This autowave is stable in a certain region of parameter values of the optical pump.

In general, the realization of dissipative structures in solids requires a high power dissipation density, at which nonlinear effects become important. Even at comparatively low pump levels, paramagnetic spin systems exhibit a nonlinearity due to, for example, magnetic saturation under dynamic polarization conditions, provided that the spin-lattice relaxation rate τ_{eL}^{-1} is sufficiently low. From this standpoint, magnetically mixed (semimagnetic) semiconductors[1] are promising materials for the realization of dissipative structures. For example, an optical bistability arises in magnetically mixed semiconductors during pumping with an energy $h\nu \approx E_g$ (at equilibrium, $h\nu < E_g$) at an intensity sufficient for a red shift of the fundamental absorption edge E_g such that the optical absorption coefficient $\alpha = \alpha(h\nu - E_g)$ is sharply increased. In the common case of magnetically mixed cubic semiconductors of the $A^2_{1-x}Mn_xB^6$ type, this shift results from a change in the giant spin splitting of energy bands,[1] which is proportional to the dynamic polarization ΔP of localized spin moments during an exchange scattering of photoexcited holes by these moments (the photoexcitation is by π-polarized light). The electrons excited in the process do not participate in exchange scattering with a flip of localized spin moments, and they drop out of the picture.[2]

For a crystal which is thin (in comparison with α^{-1}), the deviation ΔP from the equilibrium value (P_0) of the spin polarization of the localized spin moments is determined by the ratio of the rate of production of spin-nonequilibrium electron-hole pairs to the spin-relaxation flux[1] $n_l \tau_{eL}^{-1}$ (n_l is the concentration by volume of localized spin moments). The situation changes qualitatively in the case of bulk samples, if the optical power is not sufficient to cause a substantial change in P throughout the crystal. In this case, a comparatively small region of the magnetically mixed semiconductor, with a locally increased magnetization, remains away from equilibrium. In this region, there is a narrowing of the band gap E_g, and most of the radiant energy is absorbed here. A local variation of the magnetization far from the faces of a crystal moves opposite the optical flux as a result of spin diffusion in the semiconductor, dividing the crystal into waiting, excited, and depressed (shadow) regions. An analysis of the conditions for the occurrence of this effect includes the derivation of an equation for ΔP, a search for autowave solutions, and an analysis of their stability.

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In general, a kinetic equation for the polarization of the localized spin moments, P, is derived from the system of equations for ΔP and for the polarization P_h and the density n_h of the photoexcited holes. If P is treated as a slow variable, to which the fast variables P_h and n_h are subordinate, and if the hole diffusion length is assumed to be short, $L_{h,es} = (D^h \tau_{es}^h)^{1/2} \ll \alpha_{max}^{-1}$ (τ_{es}^h is the time of the exchange scattering of holes by localized spin moments in the magnetically mixed semiconductor, $\tau_{es}^h \sim 10^{-10} - 10^{-11}$ s), then a closed equation can be derived for ΔP. This equation, which incorporates the generation, spin-relaxation, and spin-diffusion processes, is

$$\frac{\partial \Delta P}{\partial t} = \frac{2\Sigma^*(\Delta P)}{n_l} - \Delta P \tau_{eL}^{-1} + D_s \frac{\partial^2 \Delta P}{\partial r^2}, \quad \frac{\partial \Delta P}{\partial r}\Big|_{\substack{r=r_f \\ r=r_b}} = 0, \tag{1}$$

where

$$\Sigma^*(\Delta P) = (I_0/h\nu)\alpha(G_m^\pi \Delta P - \Delta E_0) \exp\{-\int_{r_f}^{r} \alpha(G_m^\pi \Delta P' - \Delta E_0)\, dr'\},$$

r_f is the coordinate of the "front" face of the crystal, through which the radiant energy flux of density I_0 passes, D_s is the spin diffusion coefficient in the light propagation direction, $\Delta E_0 = E_0^\pi - h\nu$, E_0^π is the energy of the band–band transition which is active in the π polarization at a nonsaturating $P = P_0$ and G_m^π is the shift E_0^π in the limit $P \to 1$.

The wave solution $\Delta P(r,t) = \Delta P(r - Vt)$ satisfies Eq. (1) approximately under the following two conditions: (1) The autowave is far from the front of the crystal (r_f) and far from its back (r_b). (2) $\alpha^{-1}(\Delta E_0) \gg r_2 - r_1$, where $r_2 - r_1$ is a scale width of the autowave. Equation (1) is analogous to the equation for a concentration domain[3] and can be rigorously reduced to an equation for the self-similar variable $\zeta = r - Vt$, if these conditions are exaggerated, through the assumptions $r_f \to -\infty$, $r_b \to \infty$, and $\alpha(-\Delta E_0) = 0$. Furthermore, analysis shows that the properties of $\Delta P(\zeta)$ are reflected qualitatively by the approximation $\alpha(y) = \lambda^{-1}\Theta(y)$ [$\Theta(y)$ is the unit step function], so that (1) can be rewritten

$$\hat{L}\Delta P = \begin{cases} -\beta \exp[z_1 - z], & z_1 \leqslant z \leqslant z_2 \\ 0, & z < z_1,\ z > z_2 \end{cases} \tag{2}$$

$$\hat{L} = d\frac{\partial^2}{\partial z^2} + v\frac{\partial}{\partial z} - 1,$$

where $d = D_s \tau_{eL} \lambda^{-2}$, $v = V\tau/\lambda$, $\beta = 2I_0 \tau_{eL}/h\nu n_l \lambda$ ($(\Delta E_0/G_m^\pi) - P_0$), $z = \xi/\lambda$, and z_1 and z_2 are the roots of the equation $\Delta P(z) = \Delta E_0/G_m^\pi$ (Fig. 1). The condition that the solutions of Eq. (2) be continuous in terms of the function and its derivative at the points z_1 and z_2 gives us equations for determining v and $\Delta z = z_2 - z_1$ for all values of the reduced pump level β, so that the characteristics of the autowave, $\Delta P(z)$, can be determined completely. Figure 2 shows numerical solutions of these equations. These solutions reflect the physical essence of the problem: The autowave moves opposite

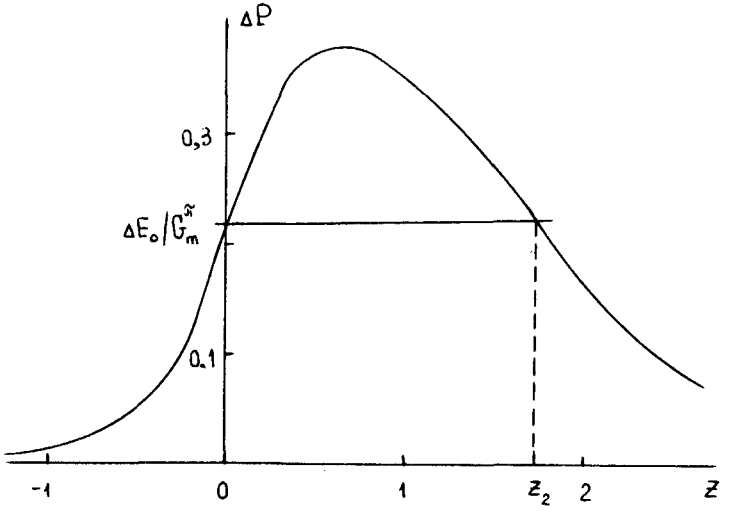

FIG. 1. Shape of the autowave of Eq. (2). This curve is plotted for $\beta = 4.63$ and $d = 0.3$; these values correspond to $v = -0.5$ and $z_2 = 1.77$. In the coordinate system used here, we have $z_1 = 0$.

($V < 0$) the light flux. The very existence of the autowave is possible only if the pump level is sufficiently high, $\beta > \beta_m$. The curve $\beta_m = \beta_m(d)$ serves as a phase diagram of equilibrium systems, singling out the region of values of β and d for which the excitation of an autowave is possible (Fig. 3). The behavior of the width of the autowave, Δz, as a function of β and d is qualitatively similar to the dependence $v = v(\beta,d)$ (Fig. 2). The limiting values V_m and Δz_m correspond to the same values of β and d. An analysis of the stability of the autowave with respect to fluctuations Δr, carried out

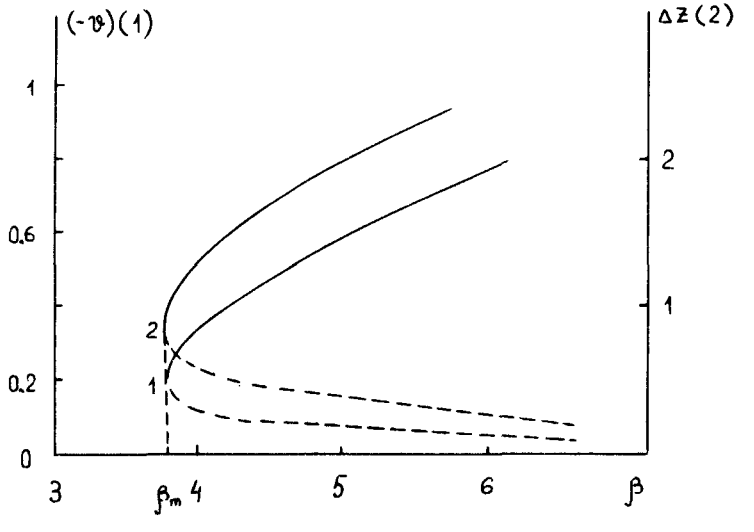

FIG. 2. Plots of (1) $v(\beta)$ and (2) $\Delta z(\beta)$. $d = 0.3$. Solid line—Stable autowaves.

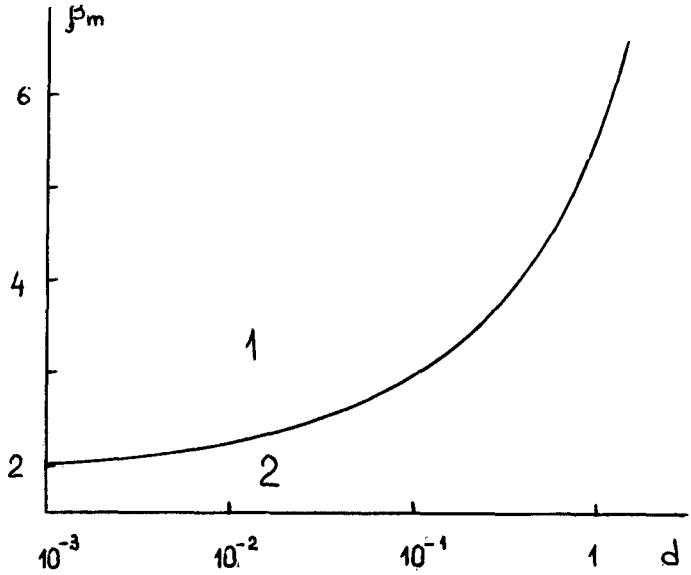

FIG. 3. Plot of $\beta_m(d)$. The excitation of autowaves is possible in region 1.

with the help of general equation (1), has shown that solutions which correspond to the lower branches of the $v(\beta)$ curves [or the $\Delta z(\beta)$] are unstable, while solutions which correspond to the upper branches of the corresponding curves, and which describe the increase in the velocity of the autowave along with its width with increasing intensity of the optical pump, are stable.

In summary, this study has shown that a spin-polarization autowave can indeed be realized in a magnetically mixed semiconductor under certain optical pumping conditions. Observation of the motion of this wave on the basis of the radiative recombination of carriers after their exchange scattering by localized spin moments would make it possible to, in a sense, visualize the spin diffusion in disordered magnetic materials of this type. Numerical estimates derived with the help of the results above show that in a magnetically mixed semiconductor with $E_g = 2.5$eV, $x = 2\times10^{-3}$, $\tau_{eL} = 10^{-3}$s, $\lambda = 1\mu$m and $d < 0.1$ the pump power density required for the excitation of an autowave would be no lower than $I_0 = 1.5$ W/cm^2. The velocity of the autowave would be no lower than $V = 0.02$ cm/s.

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[1]S. M. Ryabchenko, Izv. Akad. Nauk SSSR. Ser. Fiz. **46**, 440 (1982).
[2]Yu. G. Semenov, Fiz. Tekh. Poluprovodn. **20**, 1829 (1986) [Sov. Phys. Semicond. **20**, 1148 (1986)].
[3]V. A. Kochelap and V. N. Sokolov, Kvant. Elektron. (Moscow) **13**, 48 (1986) [Sov. J. Quantum Electron. **16**, 27 (1986)].

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