Slow and rapid motions of domain walls in a multivalley semiconductor

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The temperature dependence of the rate at which electrons are trapped by donor centers causes the domain walls formed in the multivalued Sasaki effect to become layers of a concentration depletion or enrichment. The result is either a "self-localization" of the wall at the inhomogeneity which it itself creates (a sharp decrease in the mobility in a transverse magnetic field) or a spontaneous motion of the wall.

We consider a two-valley semiconductor (Fig. 1) with a current which flows strictly in the plane of the axes of the valleys along the symmetry axis (the x axis). In a semiconductor of this sort, under conditions corresponding to the multivalued Sasaki effect,[1] there may be, in addition to the case of a spatially uniform transverse field $E_y = \vartheta E_x$ (E_x is the given extracting field), distributions $\vartheta(y)$ in the form of domain walls separating regions of a uniform field $\vartheta = \pm \vartheta_d(E_x)$. The domain walls come in two types: 1) thin walls, which separate domains with transverse fields which are directed away from the wall; 2) thick walls, which separate domains with fields directed toward the wall.[2] The length scale of the latter is determined by the electron drift length in the field $\vartheta_d E_x$ over the intervalley scattering time.

Since the electrons in domains are primarily in that valley in which their heating is relatively slight, because of the cooling effect of the transverse field, the electrons in a wall are on the average hotter than the electrons in the domains separated by the wall. The density of free electrons is a rather sharp function of their average energy, since the multivalued Sasaki effect occurs at low temperatures, where the carriers are mostly frozen, and the heating of electrons by the electric field leads to a change in the rate at which the electrons are trapped by free donors. As the heating is increased, this rate may either decrease or increase.[3] Consequently, a domain wall may acquire either an excess or a deficiency of electrons in comparison with the periphery. The effect is particularly pronounced in a thick wall because of its large size.

Since the time scale of the trapping of electrons by donors is usually significantly longer than the intervalley-scattering time of the electrons, the density irregularity which arises in this manner (like a given doping inhomogeneity[4]) is capable of both localizing a domain wall at itself and making a rest state of the wall impossible. As was shown in Ref. 4, a thick wall can be trapped stably only by a density minimum, and a thin wall by a density maximum. Accordingly, in the field region in which the rate at which electrons are trapped by donors increases with increasing heating of the electrons, a thick domain wall forms a region of a density deficiency, at which it localizes stably. In a region of fields with the opposite dependence of the trapping rate on the

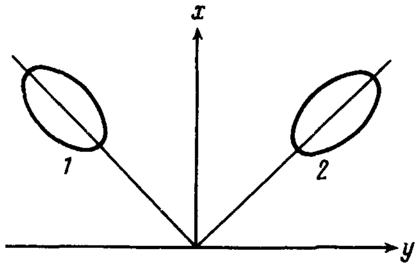

FIG. 1. Two-valley model.

heating, a steady-state position of a thick wall cannot be realized, since the wall continuously moves away from the density excess which it has created. In other words, the wall is in a state of a rather rapid spontaneous motion along or opposite the y axis.

If there is a weak magnetic field normal to the xy plane, or if there is small transverse current i_y (which would appear, in particular, if there were a small deviation of the direction of the current from the x axis), there are again no solutions in the form of steady-state domain walls in a density-homogeneous semiconductor, although there can be walls which are moving at a velocity proportional to the Hall angle or to the transverse current and which have a velocity on the order of the drift velocity in the Hall field or in the field due to the transverse current i_y . Taking account of the self-consistent density inhomogeneity which is caused by the temperature dependence of the rate at which electrons are captured by donors, we can add quite a bit to the picture drawn above.

Writing continuity equations for the electron fluxes in valleys 1 and 2 and at the donor levels (in the quasineutrality approximation), we find a solution of these equations in the form of steady-state waves which are propagating along the y axis. We assume a local field dependence of the times over which electrons move from one valley to another, τ, and for the times of trapping to a donor level, ν^{-1}. We assume that both times are functions of the effective fields $E_{1,2}$, which are given by

$$E_{1,2}^2 = E_x^2 + E_y^2 \pm 2aE_xE_y, \qquad (1)$$

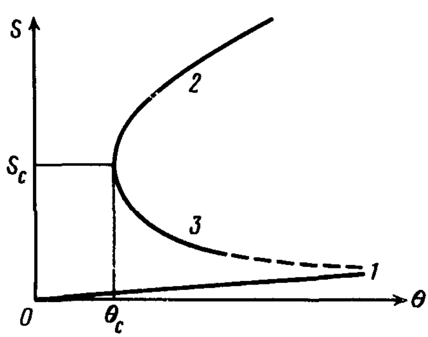

FIG. 2. Velocity of (1) slow domain walls and (2, 3) fast domain walls versus the Hall angle (for the case of a deficiency).

where $a = |\mu_{yx}^{(1,2)}/\mu_{yy}^{(1,2)}| = |\mu_{xy}^{(1,2)}/\mu_{xx}^{(1,2)}|$; $\hat{\mu}_{1,2}$ are the mobility tensors of the electrons in the valleys; and the specific functional dependences $\tau(E_{1,2})$ and $\nu^{-1}(E_{1,2})$ can be found by numerical simulation[1] or estimated from experimental data.[3]

Figure 2 is a qualitative plot of the velocity of a thick domain wall versus the Hall angle θ in the case of a deficiency in the electron density at the wall. There are three branches here. Branch 1 (a "slow" wall) corresponds to a quasisteady motion of a thick wall along with a self-consistent density profile. The motion is slow here because of the charge exchange of donors which accompanies the motion of the wall. The velocity of this slow motion, with open-circuited Hall electrodes, is given by

$$S_1 = -\theta\mu E_x \frac{\nu(E_x)\tau(E_x)}{\kappa(E_x)g(E_x)}\left\{1 + \frac{1+\nu(E_x)\tau(E_x)/2}{g(E_x)} - \frac{a^2}{2}\frac{E_x}{\nu(E_x)}\nu'(E_x)\right\}, \quad (2)$$

where

$$\mu = \mu_{xx}^{(1,2)} = \mu_{yy}^{(1,2)}, \quad g(E_x) = g_0(E_x)/(1+\kappa(E_x)),$$

$$g_0(E_x) = -\left[1 + \frac{a^2E_x}{\tau(E_x)}\tau'(E_x)\right] + \frac{\tau(E_x)}{2}[a^2E_x\nu'(E_x) - \nu(E_x)],$$

$$\kappa(E_x) = -\frac{a^2}{2\nu(E_x)}[(1+a^2)E_x\nu'(E_x) - a^2E_x^2\nu''(E_x)];$$

the primes mean the derivatives with respect to E_x. We recall that the multivalued Sasaki effect occurs if $d\tau/dE_x < 0$; the condition $g_0(E_x) > 0$ must hold. A density deficiency in a wall occurs if $\kappa < 0$ (but $|\kappa| < 1$ by some margin). The motion of the wall becomes slower as the quantity $\nu(E_x)\tau(E_x) \ll 1$ becomes smaller.

Branches 2 and 3 in Fig. 2 correspond to a "fast" wall, whose velocity is determined by the roots of the quadratic equation

$$S^2 - 2\frac{\theta}{a}pS - q = 0, \quad (3)$$

where

$$p(E_x) = a\mu E_x[1 + (1+\nu(E_x)\tau(E_x)/2)/g_0(E_x)],$$

$$q(E_x) = (a\mu E_x)^2\tau(E_x)\left[\frac{1}{2}(\nu^+ + \nu^-) - \nu(E_x)\right]/g_0(E_x),$$

and $\nu^{\pm} = [1 \pm (\vartheta_d/a)]\nu(E_x\sqrt{1+\vartheta_d^2 \mp 2a\vartheta_d})$. Deep in the field interval with the multivalued Sasaki effect we have $\vartheta_d \approx a$, and the expression in square brackets in the expression for $q(E_x)$ is equal to $\nu(E_x\sqrt{1-a^2}) - \nu(E_x)$. In a wall with a density deficiency we have $q(E_x) < 0$. At $\theta < \theta_c(E_x) = a|q|^{1/2}|p$, a fast motion of a wall is thus impossible. Motion involving a detachment from a density deficiency becomes possible only at $\theta > \theta_c$. The velocity of this motion is high, and the deficiency accom-

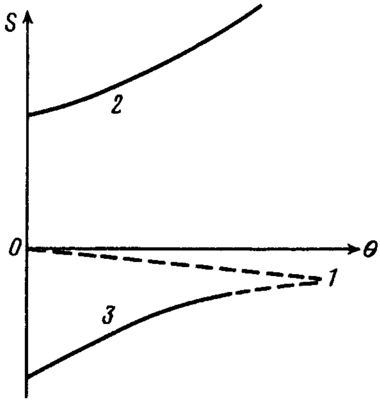

FIG. 3. The same as in Fig. 2 (for the case of an excess).

panying the wall does not manage to develop. Of the two velocities of the fast motion of a wall, one increases with increasing θ. At $\theta \gg \theta_c$ we have $S_2 \propto \theta$. The other velocity of the fast motion falls off with increasing θ (at $\theta \gg \theta_c$, it falls off as $1/\theta$).

Figure 3 shows the qualitative motion of a wall with an excess electron density. In this case we have $\kappa > 0$, and the slow wall is moving in the direction opposite that in the preceding case. However, a slow wall with an excess is unstable. Fast walls (branches 2 and 3), on the other hand, exist in this case even at $\theta = 0$: This is a spontaneous motion of a wall, which moves away from the inhomogeneity that it creates (an enrichment region). In contrast with the preceding case, the fast walls move in opposite directions. One of them is accelerated by the magnetic field, so that at $\theta \gg \theta_c$ we again have $S_2 \propto \theta$, and there is a complete freeing from the density shell. The other wall is retarded.

In the case with a Hall current the picture of the motion of the walls remains qualitatively the same, but the direction of the slow motion may reverse.

Some recent experiments[5] have revealed oscillations in the emf at end probes at a frequency proportional to the magnetic field. These oscillations might be interpreted as resulting from a slow motion of a multidomain structure in n-Si. However, the present paper on the motion of isolated domain walls is inadequate for a complete description of the motion of multidomain structures.

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