DOMAIN STRUCTURE OF MULTIVALLEY SEMICONDUCTOR IN THE MULTIPLY-VALUED SASAKI EFFECT

Z.S. Gribnikov and V.V. Mitin
Institute of Semiconductors, USSR Academy of Sciences
Submitted 1 July 1971
ZhETF Pis. Red. 14, No. 4, 272 - 276 (20 August 1971)

The rapid decrease of the time τ of intervalley scattering with increasing electron energy in multivalley semiconductors leads to a definite region of heating fields and to the existence of not one but several stable distributions of the electrons among the valleys, corresponding to different values of the transverse fields (the multiply-valued Sasaki effect [1 - 4]). The presence of several stable solutions of the spatially-homogeneous problem can lead to the existence in real samples of a domain structure whereby the sample breaks up into regions in each of which there is realized one of the stable distributions. Such a structure should be determined by the configuration of the sample and by the boundary conditions on its surface. In samples that are homogeneous in the current direction, the boundaries between the domains should be parallel to the current lines (in the absence of a negative differential resistance of N-type).

We shall show below that in the simplest two-valley case, which can be realized in anisotropically-deformed n-Si and n-Ge (in the latter with insignificant modification), only single- and two-domain structures are stable for samples in the form of plates, and the multidomain solutions are unstable.

We consider a symmetrical direction of the current in a sample having the form of a plate $-d \le y \le d$ (Fig. 1), with the field E_x, assumed given, chosen such that in the homogeneous case there exist only two stable values of the transverse field E_y, namely $E^+ > 0$ and $E^- = -E^+ < 0$. In the field region under consideration, the spatial distributions of the 1- and 2-electrons ($\mu_{yx}^{(1)} = 0$, $\mu_{yx}^{(2)} = -\mu_{yx}^{(1)} > 0$) is determined by two characteristic lengths, viz., the stretched length $L_E \sim \mu\tau E^+$ and the compressed length $\ell_E \sim \bar{\varepsilon}/eE^+$, where $\bar{\varepsilon}$ is the average electron energy. $L_E >> \ell_E$ if the conditions for the independence of the energy balance of the valleys (assumed in [4] in the analysis of the spatially-homogeneous solutions) are satisfied. Therefore, the field E_y experiences abrupt changes in small intervals, called domain walls, and varies smoothly in the remaining part of the semiconductor, i.e., in the domains. In the latter we can neglect the diffusion components of the transverse carrier fluxes, as well as all other components of these fluxes connected with the gradients of the distribution-function parameters, and only their field components need be taken into account in the fields E_x and E_y. Then the continuity equation for the difference flux $j_y^{(1)} - j_y^{(2)}$ (under the condition that $i_y = e(j_y^{(1)} + j_y^{(2)} = 0)$ takes the form

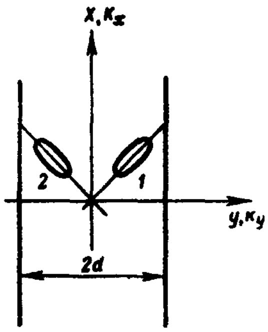

Fig. 1

$$\frac{dy}{d\zeta} = \frac{aE_x\zeta\Psi(\zeta)}{\zeta - L(\zeta)} \equiv F(\zeta), \quad (1)$$

where

$$\zeta = \frac{E_y}{aE_x}, \quad a = \left|\frac{\mu_{yx}^{(1,2)}}{\mu_{yy}^{(1,2)}}\right|, \quad L(\zeta) = \frac{\chi + \beta}{1 + \chi\beta},$$

$$\chi = \frac{\mu_1 - \mu_2}{\mu_1 + \mu_2}, \quad \beta = \frac{r_1 - r_2}{r_1 + r_2}, \quad \mu_{1,2} = \mu_{xx}^{(1,2)} = \mu_{yy}^{(1,2)},$$

$$\Psi(\zeta) = -\frac{1}{2\zeta(\tau_1^{-1} + \tau_2^{-1})}\frac{1-\zeta\chi}{1+\beta\chi}\frac{d}{d\zeta}\left[(\mu_1 + \mu_2)\frac{(1-\chi^2)(1-\zeta^2)}{1-\zeta\chi}\right].$$

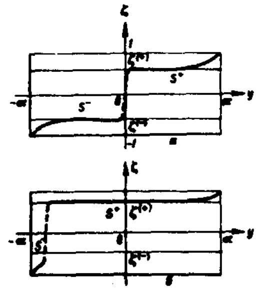

Fig. 2

We note that $\Psi(\zeta)$ is an even function of ζ; for μ independent of the heating power, when $d\mu_{1,2}/d\zeta = 0$ and $\chi = 0$, we have $\Psi(\zeta) = (\mu_1 + \mu_2)/(\tau_1^{-1} + \tau_2^{-1})$. The function $L(\zeta)$ is odd, and the equation $\zeta = L(\zeta)$ coincides with Eq. (8') of [4], which determines the stationary homogeneous solutions. At the considered values of E_x this equation has three solutions: $\zeta = 0$ (unstable) and $\zeta^{(\pm)} = E^{\pm}/aE_x$. Inasmuch as $dy/d\zeta \to \infty$ as $\zeta \to \zeta^{(+)}$ and as $\zeta \to \zeta^{(-)}$, Eq. (1) has solutions of three types, and we shall accordingly consider three types of domains:

1) S^+ domains, in which $1 \geqslant \zeta > \zeta^{(+)}$ и $y - y(1) = -\int_\zeta^1 F(\zeta)\,d\zeta$; (2)

2) S^- domains, in which $-1 \leqslant \zeta < \zeta^{(-)}$ и $y - y(-1) = \int_{-1}^{\zeta} F(\zeta)\,d\zeta$; (3)

3) M domains, in which $\zeta^{(+)} > \zeta > \zeta^{(-)}$ и $y - y(0) = \int_0^{\zeta} F(\zeta)\,d\zeta$. (4)

The M-domains can be subdivided into parts: $\zeta^{(+)} > \zeta > 0$ (M^+ domains) and $0 > \zeta > \zeta^{(-)}$ (M^- domains), separated by a broad domain wall (the dimensions of which is of the order of the stretched rather than the compressed length).

The $\zeta(y)$ dependence in a sample with specified boundary conditions consists of domain sections given by formulas (2), (3), and (4), volume domain walls separating the domains, and surface domain walls that match the domains to the boundary conditions. In the considered case of symmetrical direction of the current in the sample, the following condition should be satisfied on the volume domain wall

$$\zeta(y_c - 0) = -\zeta(y_c + 0), \tag{5}$$

where y_c is the coordinate of the "center" of the wall. According to this condition there can coexist in one sample either only S^- and S^+ domains, or only M^- and M^+ domains, while structures including both $S^\pm$ and $M^\pm$ domains are forbidden.

A multidomain structure consisting of $S^\pm$ domains should include both S^-S^+ walls[1)] and S^+S^- walls. It is easy to note that the latter, unlike the former, are unstable against small displacements from their equilibrium position satisfying the condition (5). Violation of condition (5) when the wall is displaced leads to the appearance of flux differences $j_y(y_c + 0) - j_y^{(1)}(y_c - 0)$ and $j_y^{(2)}(y_c + 0) - j_y^{(2)}(y_c - 0)$, which strive to restore the satisfaction of condition (5) in the case of an S^-S^+ wall and to increase the flux difference in the case of an S^+S^- wall. Thus, the stationary solutions with S^+S^- walls (if they exist) are unstable, and consequently a multidomain structure of $S^\pm$

---

1)The S^-S^+ wall separates an S^- domain at $y < y_c$ from an S^+ domain at $y > y_c$.

domains is impossible. It is similarly possible to demonstrate the instability of an M^-M^+ wall (whereas an M^+M^- wall is stable if stationary solutions with such a wall exist).

From the instability of the M^-M^+ and $\dot{S}^+S^-$ walls it follows that only six simplest domain-structure types are possible in plates: four single-domain structures (S^-, S^+, M^-, and M^+ structures with domain walls only near the surface) and two two-domain structures, S^-S^+ and M^+M^-. The S^-S^+ structure contains a thin domain wall. As to the M^+M^- structure, it may be also without such a wall, i.e., it can represent a continuous M domain (with a broad domain wall).

Let us consider the case when there are no surface scattering mechanisms whatever on either of the surfaces $y = \pm d$ (this occurs, for example, in the case of strong depletion of carriers from the surfaces). It then follows from the conditions $j_y^{(1,2)}(\pm d) = 0$ that $\zeta^2(\pm d) = 1$, and a two-domain S^-S^+ structure is realized in the sample with a domain wall in the center of the plate (Fig. 2a). In this structure the transverse Sasaki emf is exactly equal to zero, since the emf's in the different domains only cancel each other. It should be noted, however, that in thick samples ($d \gg L_E$) the position of the domain wall in the middle of the plate is practically unrealizable, since very small deviations of the current direction from exact symmetry causes a strong displacement of the wall from the central plane towards one of the surfaces of the sample. This realizes a quasi-single-domain S^-S^+ structure (Fig. 2b), in which one of the domains has a thickness on the order of several lengths L_E, whereas the other encompasses practically the entire sample.

The domain structure considered here differs from the domain structure investigated in [5]. In the latter, for the two-valley case, a narrow domain wall occurs only for $d \lesssim L_E$, whereas here it can exist in arbitrarily thick samples.

The authors thank E.I. Rashba and I.B. Levinson for useful critical remarks.

[1] H. Reik and H. Risken, Phys. Rev. 126, 1737 (1962).
[2] H. Shyam and H. Kroemer, Appl. Phys. Lett. 12, 283 (1968).
[3] E. Erlbach, Phys. Rev. 132, 1976 (1963).
[4] Z.S. Gribnikov, V.A. Kochelap, and V.V. Mitin, Zh. Eksp. Teor. Fiz. 59, 1828 (1970) [Sov. Phys.-JETP 32, 991 (1971)].
[5] Z.S. Gribnikov, V.A. Kochelap, and E.I. Rashba, ibid. 51, 266 (1966) [24, 178 (1967)].