Wannier–Stark localization in a superlattice of hexagonal silicon carbide

V. I. Sankin and I. A. Stolichnov
A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences,
194021 St. Petersburg, Russia

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A negative differential resistance with threshold fields of 500, 1200, and 2000 kV/cm and also a resonant tunneling with a threshold field of 1800 kV/cm have been observed in a hexagonal crystal with a natural 6H-SiC superlattice. Analysis of the experimental data shows that these effects can be regarded as manifestations of Wannier–Stark states with various degrees of localization. These results support the position that Wannier–Stark "ladders" exist. This position has come under doubt because of the possibility of an interband mixing of electron states by an electric field.

A possible localization of electron states in a strong electric field was first demonstrated by Wannier[1] in 1959. However, the existence of a Wannier–Stark localization is still a matter of sharp debate; the very existence of this localization has itself been questioned in certain papers. The strong controversy (some recent papers[2–5] can serve as examples) demonstrates the importance of this problem to the physics of the crystalline state. The acute need for experimental data on this problem is obvious.

For a fairly long time, the research on Wannier–Stark localization was restricted to AlAs–GaAs heterojunction superlattices. Some optical spectra recorded in 1988 demonstrated that discrete electron states can arise in an electric field.[6,7] It would seem that a negative differential resistance induced by Wannier–Stark quantization should be found in such entities. However, the only results obtained along this direction are in the papers of two groups, in France[8] and the U.S.[9] Their results have been interpreted in the theory developed by Esaki and Tsu,[10] but we believe they can also be interpreted in other ways, without invoking Wanner–Stark localization. Moreover, the data reported in Refs. 8 and 9 do not agree with each other either qualitatively or quantitatively. The problems which confront efforts to study Wannier–Stark localization in artificial superlattices may stem from a fundamental shortcoming of these superlattices, namely, the presence of interfaces between layers. These interfaces cause a scattering of electrons, which is capable of suppressing effects of Wannier–Stark localization in electron transport.

This difficulty can be eliminated by using a natural superlattice, which arises as the result of a local nonequivalence of atoms in certain uniaxial crystals with a large unit cell. Among crystals in this category, the most common and most stable is silicon carbide, SiC, which exhibits a variety of crystalline forms or so-called polymorphs. The high quality of the natural superlattice, which is free of interfaces, the possibility of varying the constant of the superlattice by varying the polymorph, and the high breakdown fields make SiC a unique entity for studying Wannier–Stark localization.

A detailed study of this localization in a superlattice requires satisfying certain

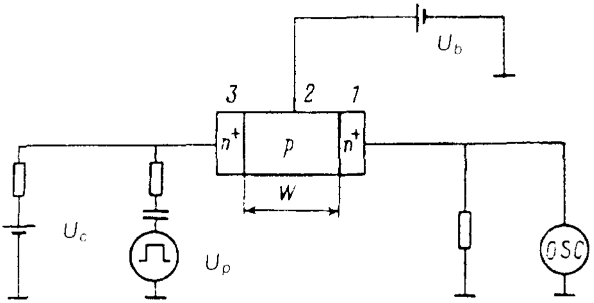

FIG. 1. Schematic circuit of the measurements.

conditions. The hole component of the current must be eliminated, since the spectrum of holes is not subject to superlattice splitting. It is also necessary to eliminate the increasing dependence of the current on the field which is characteristic of conventional n^+-n-n^+ structures.

These requirements are met by a three-electrode structure which we have developed (Fig. 1). The properties and operating mechanism of this structure are described in Ref. 11. We will therefore restrict the discussion here to the basic characteristics of this structure according to Fig. 1. Junction 1 is a source of electrons (an emitter), while region 2 is an active region (the base), and junction 3 is a collector. The forward-voltage source U_b is used to alter the height of the potential barrier of junction 1. Pulsed-voltage source U_p injects electrons into region 2 and creates a quasiuniform electric field in this region. Figure 2 shows profiles of the electric field in the structure for three cases. In some previous studies[12,13] we used a version with $U_b \neq 0$, $U_p \neq 0$, and $U_c = 0$ (Fig. 2b). In that case, the major events occurred in region 2, in which the field was essentially uniform. As a result of that study, a strong negative differential resistance was found, for the first time; according to all the data, that negative resistance corresponded to the criteria given in Ref. 10.

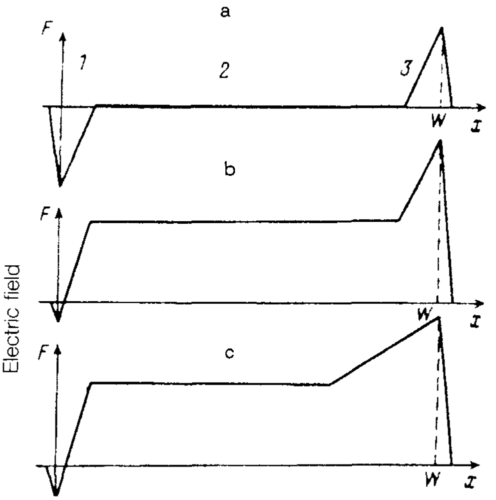

FIG. 2. Profiles of the electric field in the test structure. a—$U_b = 0$, $U_c = 0$, $U_p = 0$; b—$U_b \neq 0$, $U_c = 0$, $U_p \neq 0$; c—$U_c \neq 0$, $U_c \neq 0$, $U_p \neq 0$.

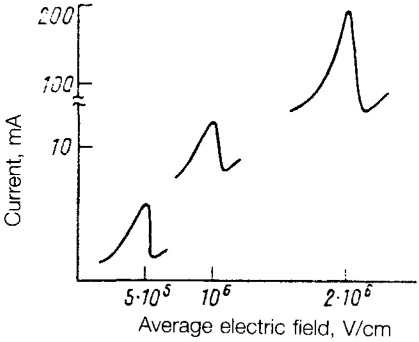

FIG. 3. Current-voltage characteristic of a 6H-SiC test structure under the conditions corresponding to Fig. 2c.

According to the theory of Wannier-Stark localization, this effect corresponds to the initial phase of the localization process if there is a sufficiently wide miniband. A higher degree of localization evidently requires increasing the electric field to values

$$F \geqslant E_1/ed, \tag{1}$$

where E_1 is the width of the first miniband, e is the charge of an electron, and d is the constant of the superlattice. According to existing estimates, these fields would have to be above 1000 kV/cm. This situation was arranged in our structure (the field profile is shown in Fig. 2c). A static bias voltage was applied to the collector–base junction, so the field was very nonuniform. For quantitative estimates we used average values of the field, which are half the maximum values in the case of a linear distribution. It was thus possible to produce fields with magnitudes above 2000 kV/cm. The role of the pulsed field was to inject electrons from the emitter into the base and to cause a drift through region 2. Consequently, a pure electron flux, without any holes, entered the strong-field region, 3.

The experiment was carried out in the following way: A pulsed current was passed through the structure by applying a pulsed voltage and by biasing the emitter–base junction in the forward direction. The static voltage U_c on the collector junction was then increased. This increase had the effect of expanding the space-charge region 3 into region 2 and causing an increase in the field in this region. As this field increased, the pulsed current through the structure increased slowly. When a certain average field was reached, however, the monotonic field dependence of the current gave way to a dependence with some sharp structural features. This effect can be seen in Fig. 3, which is a plot of the current versus the average field. These results were found only in the case of 6H-SiC. Structural features in the form of a sharp decrease in the current or, on the contrary, a sharp increase in the current were observed at average fields above 500, 1200, 1800, and 2000 kV/cm.

We believe that the most likely interpretation of these results is to be found in the theory of Wannier–Stark localization, since other theories are incapable of drawing a noncontradictory picture.

1. The negative differential resistance corresponding to the lowest threshold field, $F_t = 500$ kV/cm, should, according to the logic of the development of Wannier-Stark

localization, be caused by Bragg reflection from the edge of the miniband.[10] We found an effect with a similar mechanism in Ref. 12, but with a quasiuniform electric field. This circumstance apparently gives us a basic explanation for the significant difference between the threshold field in Ref. 12 and that which we just cited.

2. The negative differential resistance at an average field above $F_t = 1200$ kV/cm corresponds to a higher degree of localization, and it should be attributed to the case determined by condition (1). The Stark energy eF_td is 90 meV, in fair agreement with (1) if the width of the first miniband is 0.1–0.4 eV, as has been found from approximate estimates based on the results of Refs. 4 and 15. Here d is the constant of the superlattice, 7.5 Å. This estimate shows that the effect we are discussing here is probably due to a hopping mechanism for current transport between different Stark levels.[16]

3. An increase in the Stark energy to

$$F_t \geqslant E_{12}/ed, \tag{2}$$

where E_{12} is the gap between the first and second minibands, should lead to a resonant tunneling into the higher miniband. It should thus lead to a spike in the current. We have attributed the sharp increase in the current which we observed at $F_t = 1800$ kV/cm to specifically this mechanism.[17] For numerical estimates here it seems pertinent to use the value of the maximum field, $F_m = 3600$ kV/cm. In this case we have $F_med = 270$ meV, and E_{12} is, according to estimates in Refs. 14 and 15, 0.3–0.5 eV. In view of the approximate nature of these estimates, we can judge the agreement completely satisfactory.

4. The transition of electrons from the first miniband to the second is a transition from a localized state to a delocalized one. Consequently, after this transition, an electron can pass through the same localization stages in the second miniband as in the first. We therefore attribute the current decrease, which occurs when the average field is raised above 2000 keV/cm, to Bragg reflection from the edge of the second miniband.

In summary, we have proposed an alternative way to study Wannier–Stark localization, in a new group of entities: natural silicon carbide superlattices. The experimental data reported here characterize various stages in the development of this localization process. These results have drawn the first sequential picture of the development of Wannier–Stark localization up to fields close to the breakdown level. These results constitute serious experimental proof of the existence of Wannier–Stark localization in crystals. The effects of this localization observed over a broad energy range agree with Emin and Hart's conclusion[2] that Wannier–Stark "ladders" do not disappear as the result of interband mixing of electron states by an electric field.

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