



## WANNIER-STARK OSCILLATIONS IN ZENER TUNNELING CURRENTS

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**Abstract**—We have performed measurements of current-voltage characteristics at low temperatures in *p-i-n* diodes with a thin intrinsic region containing several (GaAs)<sub>5</sub>/(AlAs)<sub>2</sub> quantum wells. Under reverse bias, we found an oscillatory structure in the second derivative of the Zener tunneling current. The measurements agree well with theoretical calculations that are based on a transfer matrix approach and a realistic multi-band and multi-channel tight-binding scattering theory. The experiments show that Wannier-Stark oscillations in semiconductors occur in the d.c. current, in the regime of interband tunneling.

### 1. INTRODUCTION

Due to the progress of crystal growth techniques such as molecular beam epitaxy, high quality heterostructure devices have become widely available. In such heterostructures, many new and physically attractive properties have been found. Especially Wannier-Stark (WS) localization and Stark-ladder states in superlattices have received much attention, since they offer device applications as sub-mm emitters[1-5]. Various properties of Stark-ladder states have been studied in optical experiments employing techniques such as photocurrent, photoluminescence and electroreflectance. While these studies have shed some light on the physical mechanisms leading to WS localizations, WS resonances have not been found in transport experiments. Indeed, it is widely believed that WS resonances become too broad to be observable once interband tunneling sets in[6].

Recently, Di Carlo *et al.*[7] studied the interplay between the Zener tunneling current and the Stark-ladder states theoretically. They predicted a novel phenomenon related to WS oscillations in the Zener tunneling current. The mechanism of these WS oscillations is as follows: when a strong reverse bias is applied to a highly doped *p-i-n* diode, electrons can tunnel from the *p*-region into the *n*-region through the energy gap which leads to the well-known Zener tunneling. When the intrinsic region of the *p-i-n* diode consists of a thin superlattice, localized Wannier-Stark-ladder states form out of the mini-band states of this superlattice due to the high electric field. Consequently, the current-voltage characteristics of

the Zener current develops an oscillatory structure due to resonant tunneling through these localized Stark-ladder states.

In the present study, we have carried out measurements of the Zener tunneling current in order to clarify whether these WS oscillations occur. Our crucial finding is that the measured derivative of the Zener tunneling current, with respect to the applied voltage, shows periodic resonances as a function of the bias indeed, in reasonable agreement with the theoretical predictions. Thus, our measurements provide evidence for WS oscillations in the Zener tunneling current.

### 2. WANNIER-STARK OSCILLATIONS IN ZENER TUNNELING CURRENT

In this section, we briefly review the calculations and discuss the mechanism of WS oscillations. The calculations have been carried out involving a realistic multi-band and multi-channel tight-binding scattering theory that incorporates the periodic crystal potential and the high electric field in a *p-i-n* structure non-perturbatively[7,8]. Figure 1 shows schematically the sample structure the calculations were performed for. The present experiment, that we will discuss in the next section, was carried out with exactly that type of structure. The intrinsic region consists of seven periods of an undoped (GaAs)<sub>5</sub>/(AlAs)<sub>2</sub> superlattice and is sandwiched by 30 Å undoped GaAs spacer layers on both ends of the superlattice. This whole structure is put between 5000 Å *p*<sup>+</sup>- and *n*<sup>+</sup>-GaAs layers, doped with  $5.0 \times 10^{18}$  (Be-doped) and  $5.0 \times 10^{18}$  (Si-doped), respectively. The Zener

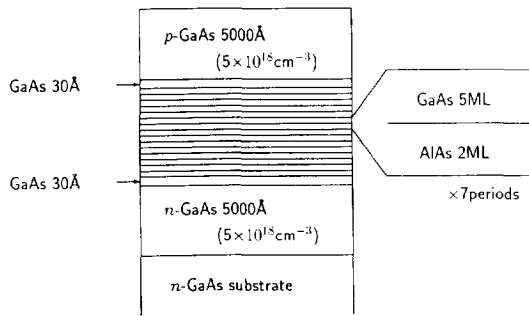


Fig. 1. Schematic sample structure used in the calculation and measurements.

tunneling current due to the electron transfer from  $p$ - to  $n$ -region is given by

$$j(V) =$$

$$\frac{-e}{(2\pi)\hbar} \int dk_{\parallel} \int dE D(k_{\parallel}, E) [f_p(E) - f_n(E - V)], \quad (1)$$

where  $-V$  denotes the applied reverse voltage. In eqn (1),  $D(k_{\parallel}, E)$  is the transmission coefficient between an in-channel state and an out-channel state. These states can be characterized by the energy  $E$  and a two-dimensional wave vector perpendicular to the electric field direction  $k_{\parallel}$ . Furthermore,  $e$  is the electronic charge, and  $f_{p(n)}(E)$  is the Fermi-Dirac distribution in the  $p$ -region ( $n$ -region). Due to the strong confinement of the electronic states in high electric fields and the Zener tunneling between valence and conduction bands, the standard transmission theory based on a one-band effective mass approximation is inadequate. Therefore, in this study, the transmission coefficient has been evaluated by using a  $sp^3s^*$  multi-band tight-binding model so as to take the mixing between different adequately into account [9,10].

Figure 2 shows a typical result of the calculation. On the left side of Fig. 2, we depict a schematic band diagram of the  $p$ - $i$ - $n$  diode with the  $(\text{GaAs})_5/(\text{AlAs})_2$

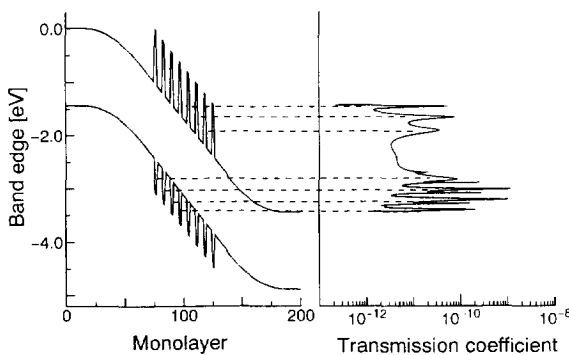


Fig. 2. Schematic illustration of Wannier-Stark oscillation in Zener tunneling current. The band diagram of the sample is shown in the left. The calculated transmission coefficient as a function of energy is shown in the right. The peaks in the transmission coefficient correspond to Wannier-Stark in the superlattice region.

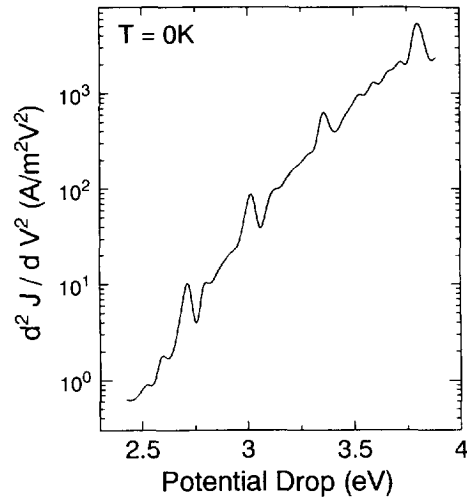


Fig. 3. Calculated second derivative of Zener tunneling current density is a  $p$ - $i$ - $n$  diode containing a  $(\text{GaAs})_5/(\text{AlAs})_2$  superlattice as function of applied reverse voltage.

superlattice and a potential drop of  $eV_D = 3.5$  eV. This potential drop corresponds to an applied bias of  $V_r = 2.02$  V according to the relation  $eV_D = eV_r + E_{\text{gap}}$ . On the right side of Fig. 2, the calculated transmission coefficient is presented as a function of energy. One can identify several peaks that reflect the enhanced Zener tunneling probability from the valence band (to the left) into the conduction band (to the right), due to resonances provided by the quantum well states that form the localized Wannier-Stark ladder states.

If one slightly increases the applied voltage, an energetically higher lying Stark-ladder state can be reached by a valence electron that tunnels from the top of the valence band into the conduction band and an additional resonance contributes to the Zener current. This additional resonance enhances the tunneling current so that another peak occurs in the total current. This explains the oscillatory structure in the Zener current.

Figure 3 shows the calculated second derivative of the Zener tunneling current density with respect to voltage for applied voltage in the range from 0.8 to 2.5 V. The peaks represent the WS resonances in the Zener tunneling current. Note that they are not equidistant. In fact, the spacing between the peaks increases with the applied voltage, which reflects the fact that the spacing between Stark-ladders increases linearly with increasing voltage.

### 3. EXPERIMENTAL RESULT AND DISCUSSION

We have carried out measurements of the current-voltage characteristics at 10 K in order to check the predictions concerning WS oscillations discussed above. The structure used in the present experiments is depicted in Fig. 1. The sample was etched into a

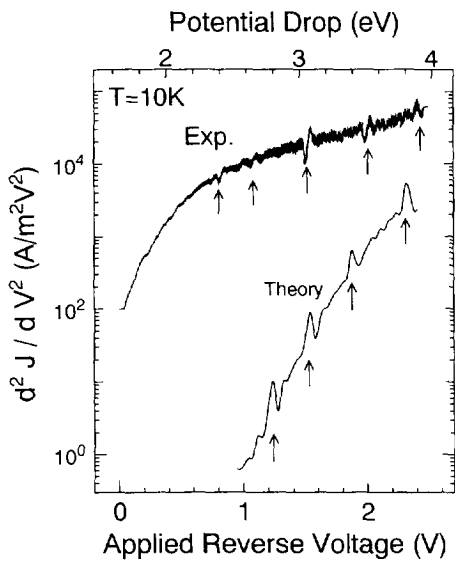


Fig. 4. Second derivative of Zener current measured at  $T = 10$  K (solid curve). Calculated result is also shown for comparison by a dashed curve.

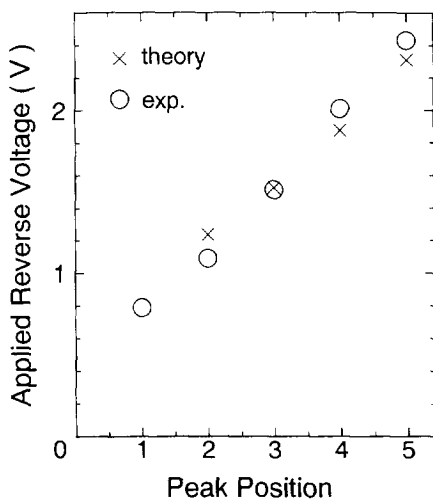


Fig. 5. Experimental and theoretical peak position in the second derivative of Zener tunneling current.

mesa structure with  $150 \times 150 \mu\text{m}$  squared shape. Figure 4 shows the second derivative of the current density as a function of the applied voltage. The solid curve and the dashed curve represent experimental and calculated results, respectively. Although the magnitude of the experimental current is much larger

than that of the calculation, the theoretical and experimental peak positions are in good agreement with one another (see Fig. 5). The discrepancy in the absolute value of the current may be due to discrepancies between the actual sample parameters (such as width of the buffer layers, doping profiles, and  $n$ - and  $p$ -concentrations) and the nominal values the calculations have been based on. Importantly, Fig. 5 shows good agreement between the observed and predicted increase in the spacing between the peaks for increasing voltage. Since this is a characteristic feature of WS oscillations, this result lends further credence to our interpretation and provides evidence for the existence of WS oscillations.

In conclusion, we have carried out Zener tunneling current measurements of  $p$ - $i$ - $n$  diodes in high electric fields. We found the second derivative of the current density to exhibit oscillations as a function of bias that are in good agreement with the theoretical calculations of Di Carlo *et al.*, who predicted WS oscillations in these structures. Thus we conclude that well localized Wannier–Stark resonances can be observed in high field semiconductor transport in the regime of Zener tunneling. This finding implies the possibility of pumping Bloch oscillations in solids not only optically, but also electrically.

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