WANNIER-STARK RESONANCES IN DC TRANSPORT AND ELECTRICALLY DRIVEN BLOCH OSCILLATIONS

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INTRODUCTION

Only recently one has been able to realize the pioneering proposal of Esaki and Tsu from 1970 to utilize Bloch oscillations in superlattices as a source for tunable coherent THz emission.1 This has been achieved by using coherent optical excitations of Bloch wave packets in superlattices and experiments indicate that the emission is superradiant.2-4 In this paper we show that coherent Bloch oscillations can be generated all electrically by using Zener (i.e., interband) tunneling as injection mechanism. In particular, we show that Bloch oscillations can maintain their coherence over many periods of oscillations in spite of the presence of strong Zener tunneling.

The stability of Bloch oscillations in the presence of interband tunneling has been a controversial subject for many years (see, e.g., Refs. 5-9). In the first part of this paper, we present both experimental and theoretical results that show that localized Wannier-Stark resonances can form in multi-quantum well structures in the presence of extremely high fields and correspondingly strong Zener tunneling. A clear evidence of Wannier-Stark resonances in carrier transport has been missing so far. Field induced tunneling between localized hole and electron states has been observed previously.10 In the second part of this paper, we utilize the stability of Wannier-Stark resonances in the interband tunneling regime to predict electrically driven Bloch oscillations in superlattices.

WANNIER-STARK RESONANCES WITH ZENER-TUNNELING

Experimentally, we have studied the current-voltage characteristics and electroreflectance of highly doped p-i-n diodes with multi-quantum well structures in the intrinsic region at low temperatures (10 K). The intrinsic zone contains 10 superlattice periods, each period consisting of 2 atomic layers of AlAs and 5 atomic layers of GaAs. The samples were processed into 150 × 150 μm² mesa structures. For an applied reverse bias voltage of 0.95 V, the self-consistent energy band profile is shown in Fig. 1(a). The corresponding electric field in the intrinsic region is ~1 MeV/cm which is very high indeed but still well below the onset of impact ionization.

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We have calculated the high field tunneling current from the p-bulk valence into the n-bulk conduction band under reverse bias, using a recently developed multi-band multi-channel scattering approach that includes the self-consistent electric field profile in the entire p-i-n structure non-perturbatively and properly accounts for the field induced interband mixing effects between valence and conduction bands\textsuperscript{11,12}. The crucial result is that the Zener tunneling current across the band gap exhibits pronounced resonances whenever the energy of an incoming valence electron and an outgoing conduction electron state is aligned with one of the Wannier-Stark resonances associated with the multi-quantum well structure in the intrinsic zone. In Fig. 1(b), we show the calculated transmission coefficient as a function of energy for the multi-quantum well structure and the field profile as displayed in Fig. 1(a). There are sharp resonances due to the quantum well states derived from the light and heavy hole and GaAs-\Gamma and AlAs-X conduction band states.

![Figure 1](image1.png)

**Figure 1.** (a) Calculated energy band profile of p-i-n structure with 10 (GaAs)\textsubscript{5}/(AlAs)\textsubscript{2} quantum wells in the 26 nm intrinsic region and an applied reverse bias voltage of 0.95 V. (b) Calculated transmission coefficient for tunneling across the band gap for this structure as a function of energy of the initial state.

![Figure 2](image2.png)

**Figure 2.** Comparison between experimental second derivative of the Zener tunneling current with the theoretical current density in the p-i-n diode of Fig. 1 as a function of reverse bias.