Evidence of Bloch Oscillations in Two-dimensional Quantum Dot Arrays

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Motivation—We investigate in this project the physics and device applications of Bloch oscillations (BOs) of electrons, engineered in high mobility quantum wells patterned into two-dimensional quantum dot arrays, i.e. quantum dot superlattices (QDSL). A BO occurs when an electron moves out of the Brillouin zone (BZ) in response to a DC electric field, undergoes Bragg reflection, and consequently, executes oscillating motion. Many efforts have been devoted to understanding and detecting BOs over the years. The main motivation behind this work is its huge potential for novel device applications; the BO frequency can fall into the terahertz (THz) regime when the magnitude of the electric field and the period of QDSL are carefully chosen. From a fundamental science perspective, studying BOs will enable us to probe high frequency many-body quantum dynamics, coherent electron transport, and energy and charge transfer. To date, no direct evidence of BO has ever been observed using electronic transport measurements. The primary reason for this is the fast damping of BOs, caused by strong electron-optical phonon scattering. We tackle this challenge by employing a new device structure, the so-called QDSL, fabricated by an interferometric lithography technique. This project is ambitious and involves both large scale nano patterning and low temperature transport measurements at DC and radio-to-THz frequencies.

Accomplishment—We have carried out current-voltage (I-V) and magnetotransport measurements in QDSL structures. In the non-linear I-V measurements, negative differential conductance (NDC) is observed. In Fig. 1, we show the I-V curve in two different samples of different electron potential modulation strength (3% vs. 15% of the Fermi energy). The observation of NDC is encouraging since it may represent the first step towards the definitive establishment of electron self-oscillations in our 2D quantum dot arrays. To understand the physical origin of NDC, theoretical simulations have been carried out. Assuming Bragg scattering for the 2D electrons at the boundary of the Brillouin zone and a relaxation time approximation, the theoretically obtained I-V curve (red) is shown in Fig. 2. The deviation from experiment at high fields may be due to the neglect of full 2D elastic scattering, or other mechanisms such as 2D domain formation.

In magnetotransport studies, a resistance spike indicative of a resonance is observed. At the present time, we believe that this resonance behavior is caused by the edge magnetoplasmon resonance. In contrast to previous experiments on edge magnetoplasmon resonances, our experiment did not apply external radiation to the quantum dot array samples. The required high frequency radiation, we speculate, is provided by the self-oscillation of electrons (i.e., Bloch oscillation) under large DC electric fields.

This research was done in collaboration with D. Li and S.R.J. Brueck at the CHTM at UNM.

Significance—We demonstrate, for the first time, negative differential conductance and evidence of Bloch oscillations in two-dimensional quantum dot arrays. This could eventually lead to the realization of frequency-tunable, solid-state THz emitters and detectors.

Sponsors for various phases of this work include: DOE Office of Basic Energy Sciences and Laboratory Directed Research & Development

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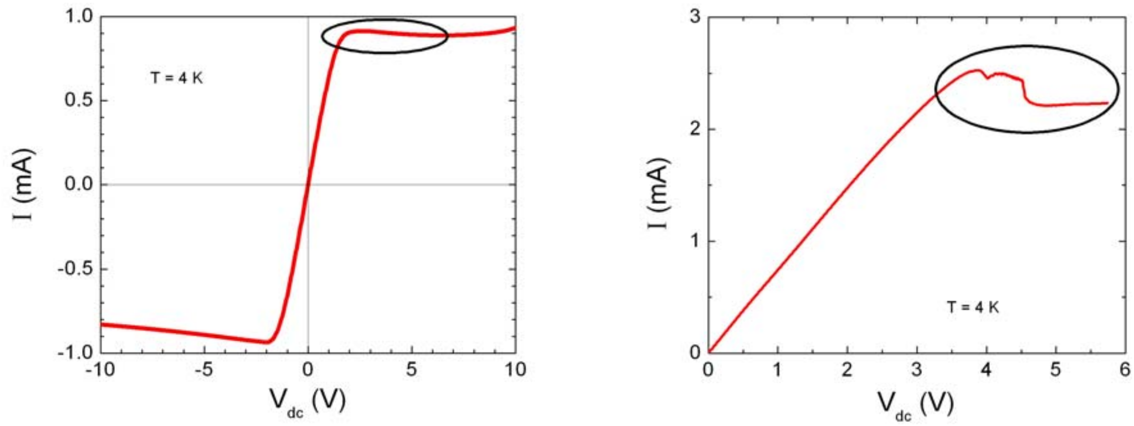

Figure 1. I-V characteristics for two samples of different electron potential modulations; a) 3% and b) 15% of the Fermi energy. In both samples, the negative differential conductance region (highlighted by circle) is seen. Current steps are also observed in the NDC region for the 15% sample. Interestingly, the I-V curve shows different characteristics in two samples. This suggests that the I-V characteristics, and probably the 2D electron dynamics, can be manipulated in a controllable way.

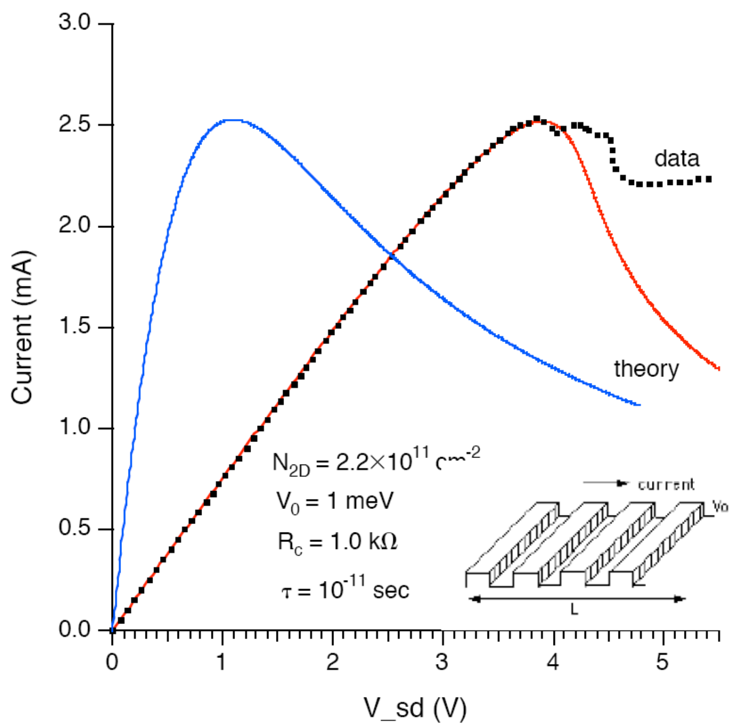

Figure 2. Theoretical result based on a relaxation-time approximation and on a 1D potential modulation, as shown in the inset. Elastic scattering is ignored. Other parameters are chosen according to real samples. The blue curve shows the result assuming no load resistance. The red curve shows the results when a proper load resistance of 1.0 kΩ is taken into account. V_0 = 1 meV corresponds to 15% modulation of the conduction band edge.