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13. ABSTRACT *(Maximum 200 words)*

This report focuses on mechanisms of negative-differential-conductance in weakly-coupled semiconductor superlattices and, in particular, on the phenomenon of sequential resonant tunneling leading to electric-field domains. Our approach involves a combination of various theoretical and experimental methods including time-resolved photoluminescence, Raman scattering and near-field-optical microscopy. A nearly complete understanding of the domain process has emerged. Specifically, a phase diagram has been established and the various parameters which control transport behavior have been identified. In photoexcited and intentionally doped superlattices, static domains dominate at high carrier concentrations while oscillations occur in a narrow density region above the regime of the quantum-confined Stark effect. Doped, although not photoexcited structures exhibit sustained GHz oscillations. The relevance of these findings to Bloch oscillations is discussed.

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SEQUENTIAL RESONANT TUNNELING AND ELECTRIC FIELD EFFECTS IN SEMICONDUCTOR SUPERLATTICES

FINAL REPORT

R. MERLIN

June 12, 1997

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FOREWORD

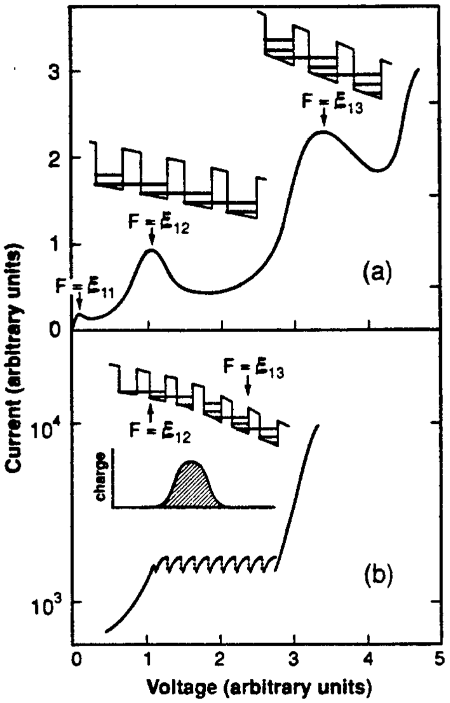
In this report, we present a brief account of research findings for projects supported by the ARO Contract No. DAAL03-92-G-0233 [Amount: $262,500, for the period May 11, 1992 through December 31, 1996]. Other than the PI, the work involved two graduate students and one undergraduate student. Some of the projects benefited from the participation of Dr. L. Schrottke, a visiting DAAD scholar from the Paul Drude Institut, Berlin (Germany) and Dr. G. Ambrazevičius, a Soros Foundation Fellow from the Institute of Semiconductor Physics, Vilnius (Lithuania).

A. ELECTRIC FIELD DOMAINS IN QUANTUM-WELL STRUCTURES

Central to the transport behavior of semiconductor superlattices (SLs) is the question of the mechanisms of negative-differential-conductance and associated instabilities [1,2]. This problem bears on phenomena as diverse as Bloch oscillations [3] and Wannier-Stark ladders [4] as well as on various aspects of nonlinear dynamics [5] and resonant tunneling [6-8]. A related but distinct question is that of the transitions between different transport modes. As it has been known for quite some time, SLs may spontaneously break into regions referred to as electric-field domains (EFD) so that the field is not uniform but piecewise constant across the sample [9-16]. However, the nature of the instability and that of the parameters which control the transition have remained largely unexplained until recently. The ARO program directed by the PI focused on this problem. His approach involved a combination of various theoretical and experimental methods including time-resolved photoluminescence (PL), Raman scattering and near-field-optical microscopy. As a result of these efforts and collaborations with the group of L. Bonilla at the *Universidad Carlos III* (Madrid, Spain) and that of K. Ploog at the *Paul Drude Institut* (Berlin, Germany), a nearly complete understanding of EFD behavior has emerged. A summary of major research findings is given below.

Domains are specific to the quantum-well (QW) regime of small miniband widths. For weakly-coupled QW structures, transport is dominated by sequential resonant tunneling [6-8]. The main regimes are illustrated in Fig. 1. At low carrier densities, the *I-V* response is of the form shown in Fig. 1 (a) with maxima at fields $\mathcal{E}_{ij}$ (i, $j \geq 1$) corresponding to the neighboring-well alignment of the ith- and jth- subbands [8]. The trace in Fig. 1 (b), analogous to the conductance data reported by

Fig. 1 - Schematic traces corresponding to (a) uniform-field (low-density) and (b) domain regimes (high density). The current maxima in (a) are due to tunneling involving the level alignment shown in the figure. In (b), the ratchet-like structure reflects the motion of the domain wall by one SL period.



Esaki and Chang [7] in 1974, reflects the presence of *microscopic* EFD [9-16]. In the course of our studies, it has become clear that the dependence shown in (b) corresponds to the high-density limit. In our time-domain PL work, we investigated the transition between the EFD and the uniform-field regime by monitoring the time behavior of a photoexcited QW-system as it evolves from (a) to (b). For this, the photoexcitation was turned on and off by switching a Pockels cell placed between crossed polarizers; our set-up gives step-like profiles with rise times of ≈ 5 ns at a repetition rate of 3.5 kHz. The data reproduced in Fig. 2 obtained in this manner show a single PL-feature at $t = 0$ which splits into two peaks corresponding to the two domains. Here, the most important point is that the peaks (as well as the photocurrent) exhibit *damped* oscillations. As shown in the inset, the fundamental frequency vs. V contains minima and discontinuities which appear to correlate with those of the steady-state photocurrent; the decay time (≈ 0.2-0.5 μs) shows a similar trend.

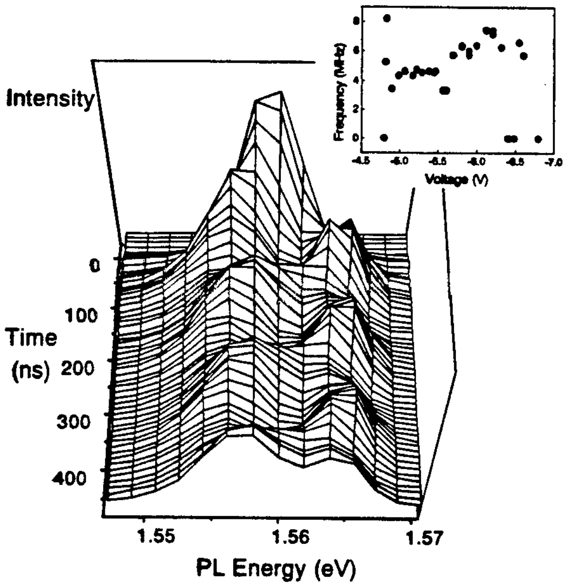


Fig. 2 - Experimental time-resolved PL for a photoexcited structure at $V = -6.21$V. Spectra are given at intervals of 10 ns. The oscillating peaks correspond to the two domains. The V-dependence of the fundamental oscillation frequency is shown in the inset.

Studies of the transport equations reveal transient oscillations, as in the PL experiments, in the range shown in Fig. 3. Furthermore, one finds stationary solutions which, depending on the parameters, have either one or three fixed points [16]. The latter case exists only for voltages between two current maxima and it corresponds to EFD. Using linear stability analyses, we determined the region shown in Fig. 3 for which EFD (uniform-field) is stable (unstable). In general, there are many solutions with a similar field profile, but with the wall displaced by one or more wells. Consistent with experiments, this gives rise to hysteresis and flat, ratchet-like traces similar to that in Fig. 1 (b).

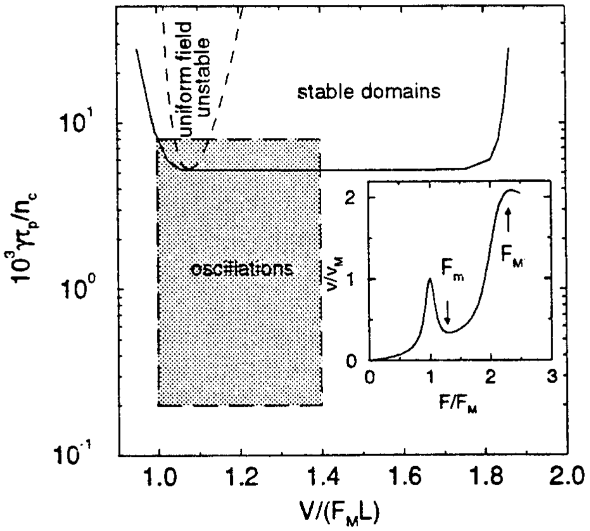


Fig. 3 - Theoretical phase diagram for a photoexcited system; γ is the photogeneration rate and V is the voltage. The shaded region denotes the range of *damped* domain oscillations. Inset: The normalized field dependence of the carrier velocity used as input in the calculations.

Results of Raman scattering from intersubband excitations for a photoexcited sample are shown in Fig. 4. As for PL [12], the spectra reveal two intersubband peaks in the EFD range. A significant feature of the data is that one can gain information on the magnitude of the charge by comparing spin- and charge-density spectra.

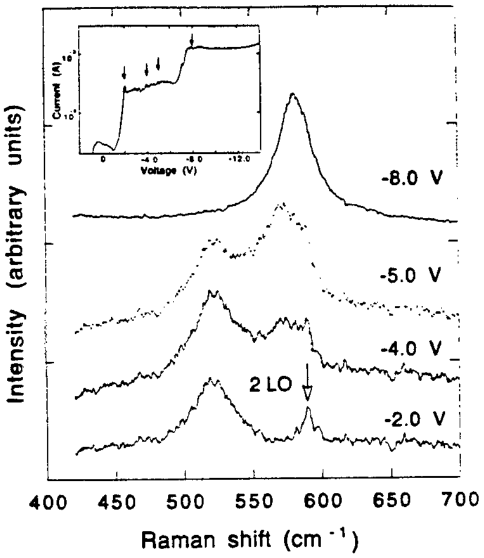


Fig. 4 - Raman spectra of a photoexcited *p-i-n* SL showing intersubband excitations. Doublets at -4V and -5V reflect the two domains in the structure. The peak labeled 2LO is due to scattering by two zone-center longitudinal optical phonons. Inset: current vs. voltage; arrows denote voltages corresponding to those of the spectra.

One of the most exciting results of this program was the discovery of self-sustained oscillations in *doped* QW-structures (we emphasize that the oscillations shown by *photoexcited* structures eventually die-out). Fig. 5 summarizes data for two different samples. The observation of oscillations suggests a link between domain instabilities and the bulk Gunn effect. However, there is an important difference in that quantum-wells allow one to tune the position and the number of tunneling maxima over a wide range by an appropriate change of growth parameters (for Gunn diodes, the important variables are mainly the sample length and the doping). While higher frequencies can possibly be achieved by careful control of the SL parameters, it remains to be seen that the instability can lead to frequencies beyond the GHz range. In this context, we notice that - with decreasing tunneling time - one would eventually approach the regime of strongly coupled samples (wide miniband-width) associated with Bloch oscillations. While our oscillations are very different in nature, we speculate that the Bloch frequency is the limiting frequency for domain instabilities.

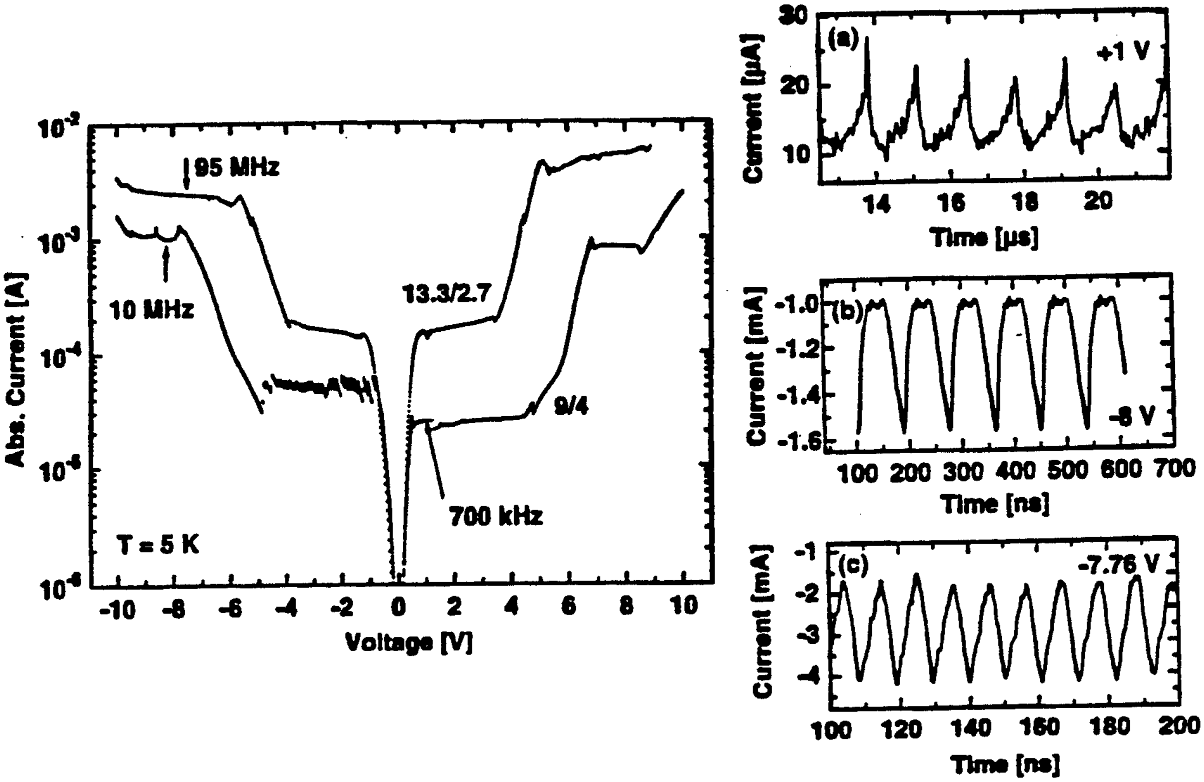


Fig. 5 - (left) *I-V* characteristics of *n*-doped superlattices *A*: 9 nm GaAs-4.0 nm AlAs and *B*: 13.3 nm GaAs-2.7 nm AlAs; (right) Current vs. time. Data for sample *A* are shown in (a) and (b), and for *B* in (c).

B. OTHER RESULTS

A few small projects unrelated to EFD research were supported by and completed during the duration of the current award. From this group, one can single out due to their importance *(i)* the Raman work on GaN and *(ii)* our theoretical studies on rotational anomalies of mesoscopic conducting rings. In the experiments on GaN films grown by MBE, we were able for the first time to obtain second-order phonon spectra. Our work on mesoscopic systems showed that, in rings threaded by a magnetic flux, the electron moment of inertia I_e exhibits a periodic pattern with maxima at $\Phi_0 = hc/e$ or $\Phi_0/2$ [modulo Φ_0] depending on the number of electrons. For slowly rotating rings, we found that I_e diverges in the limit of weak disorder. The rotational anomalies rely on the same interference mechanism responsible for persistent currents and the Aharonov-Bohm effect. More recently, we proved a simple relation between the conductivity and I_e, and showed that rotating rings carry a magnetic moment analogous to the London moment of superconductors.

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