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14. ABSTRACT
We analyze the sequential resonant tunneling model of electron transport in weakly coupled, n-doped semiconductor superlattices under a DC voltage bias. From the Poincare map, we illustrate the bifurcations of the electronic dynamics as the bias voltage is smoothly varied. We also vary the number of periods making up the superlattice, as well as the strength of (time-independent) random perturbations in the widths of the wells and barriers and (time-dependent) noise in the bias voltage and tunneling rates. We find supercritical Hopf bifurcations, period doubling bifurcations, and period doubling cascades, all of which are robust against the additional

15. SUBJECT TERMS
Quantum oscillator, periodic orbit, Poincare map, bifurcations, random number generator, Gigahertz source, frequency squeezer

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Report Title

Final Report: Research Area 11.1 ARO STIR Program: The Chaotic Quantum Oscillator

ABSTRACT

We analyze the sequential resonant tunneling model of electron transport in weakly coupled, n-doped semiconductor superlattices under a DC voltage bias. From the Poincare map, we illustrate the bifurcations of the electronic dynamics as the bias voltage is smoothly varied. We also vary the number of periods making up the superlattice, as well as the strength of (time-independent) random perturbations in the widths of the wells and barriers and (time-dependent) noise in the bias voltage and tunneling rates. We find supercritical Hopf bifurcations, period-doubling bifurcations, and period-doubling cascades, all of which are robust against the additional perturbations. These bifurcations have been predicted for single assymetric quantum wells at terahertz frequencies, but in superlattices, these bifurcations occur at gigahertz frequencies and are easier to measure.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/30/2017	1	Miguel Ruiz-Garcia, Jonathan Essen, Miguel Carretero, Luis L. Bonilla, and Bjorn Birnir. Enhancing Chaotic Behavior at room temperature in GaAs/(Al,Ga)As Superlattices, Physics Review B, ( ): . doi:
TOTAL:		**1**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
TOTAL:	

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Enhancing Chaotic Behavior at room temperature in GaAs/(Al,Ga)As Superlattices

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Jonathan Essen	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Bjorn Birnir	0.17	
FTE Equivalent:	**0.17**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Ian Jenkins	0.00	Physics
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 1.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Jonathan Essen

Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This work determines the route to chaos in weakly coupled semiconductor Superlattices as a period doubling cascade.

In particular, the first Feigenbaum constant is found with less than 1% error. In addition, a precise study of the behavior of the system for two different potential barrier heights and different number of wells shows that to reduce the number of wells and to increase the barrier height enhances chaotic behavior. It is to be noted that the reduction of the number of wells increase the frequency of oscillations since pulses get to the collector faster than in a longer SL.

These facts open a new opportunity to the development of shorter weakly coupled semiconductor SLs (possibly with more aluminium content in the barriers) with a stronger chaotic behavior and much faster oscillations. Such new electronic micrometric devices would greatly enhance the technological possibilities of random number generators.

This study makes it very likely that the period-doubling itself and the whole period-doubling cascade that produces the strange attractor can be measured at room temperature as well. This in turn makes the source, the frequency halver and squeezer and the chaotic attractor experimentally feasible. The torus mixer, cascade of quasi-periodic orbits and its resulting strange attractor can probably be found experimentally as well, but we have to redesign the SL to obtain an SL that produces them as discussed above.

In the simulations we can find the optimal parameter range for observing the above bifurcations and the resulting coherent electron states. We will be able to find the noise term that produces the optimal signal strength and we will design SLs where all of these phenomena can be easily measured.

In addition, electronic sensors such as low noise amplifiers have much higher sensitivity than optical detectors based on bolometers. We conjecture that as a result, a greater variety of dynamical structures are observable experimentally.

Technology Transfer