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14. ABSTRACT
The main objective of this collaborative project, between the University of Massachusetts Lowell and the University of Rochester, has been development of novel THz-bandwidth nanostructures based on room temperature, ballistic electron transport in 2-dimensional electron gas in III-V semiconductors. We have been working on amplifier structures using ballistic deflection transistors (BDTs) and initiated research on self-switching diodes (SSDs) that are unique planar nanostructures with diode-like characteristics. Both these ballistic

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Roman Sobolewski
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Report Title

Final Report: Ballistic deflection transistors for THz amplification

ABSTRACT

The main objective of this collaborative project, between the University of Massachusetts Lowell and the University of Rochester, has been development of novel THz-bandwidth nanostructures based on room temperature, ballistic electron transport in 2-dimensional electron gas in III-V semiconductors. We have been working on amplifier structures using ballistic deflection transistors (BDTs) and initiated research on self-switching diodes (SSDs) that are unique planar nanostructures with diode-like characteristics. Both these ballistic nanostructures are completely planar devices, thus, in ultrahigh frequency applications they do not suffer capacitance-type limitations typical for conventional semiconducting elements. The main research thrust at the University of Rochester has been development of an unique testing facility based on femtosecond laser pulses for all-optic, electro-optic, and terahertz transfer function characterization of our nanostructures with sub-picosecond resolution (THz-bandwidth). Our custom-made electro-optic sampler implements freestanding GaAs photoconductive switches with femtosecond photoresponse, as well as novel CdMnTe and CdMgTe single-crystal electrical-to-optical transducers. We performed the direct experimental verification of sub-THz BDT performance, demonstrated that SSDs were intrinsically nonlinear nanodevices capable of operating as sensitive radiation detectors, and studied, on sub-picosecond time-scale (THz bandwidth), nonequilibrium carrier dynamics of such novel materials as Si-on-glass, CdMnTe, CdMgTe, and vanadium dioxide. In parallel to our experimental effort, we have also performed extensive device physics analysis and THz circuit simulations and modeling. Our program advances research on ballistic transport nanodevices, and on THz electronics and photonics in general. Innovative educational and outreach activities have been the integral part of the program.

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
02/04/2016	4.00	J Serafini, Y Akbas, L Crandall, R Bellman, C Kosik Williams, Roman Sobolewski. Nonequilibrium carrier dynamics in ultrathin Si-on-glass films, Journal of Physics: Conference Series, (10 2015): 0. doi: 10.1088/1742-6596/647/1/012032
02/04/2016	6.00	M Margala, H Wu, Roman Sobolewski. Ballistic deflection transistors and their application to THz amplification, Journal of Physics: Conference Series, (10 2015): 0. doi: 10.1088/1742-6596/647/1/012020
02/04/2016	5.00	Y Akbas, A Stern, L Q Zhang, Y Alimi, A M Song, I Iñiguez-de-la-Torre, J Mateos, T González, G W Wicks, Roman Sobolewski. Ultrahigh responsivity of optically active, semiconducting asymmetric nano-channel diodes, Journal of Physics: Conference Series, (10 2015): 0. doi: 10.1088/1742-6596/647/1/012013
04/18/2016	8.00	Yunus Akbas, John Serafini, Lucas Crandall, Robert Bellman, Carlo Kosik Williams, Roman Sobolewski. Time-resolved, nonequilibrium carrier dynamics in Si-on-glass thin films for photovoltaic cells, Semiconductor Science and Technology, (04 2016): 0. doi: 10.1088/0268-1242/31/4/045006
09/15/2013	1.00	Martin Mikulics, Roman Adam, Detlev Grützmacher, Roman Sobolewski, Jie Zhang. Generation of THz transients by photoexcited single-crystal GaAs meso-structures, Applied Physics B, (05 2013): 0. doi: 10.1007/s00340-013-5495-1
10/23/2014	2.00	M Mikulics, H Hardtdegen, R Adam, D Grützmacher, D Gregušová, J Novák, P Kordoš, Z Sofer, J Serafini, J Zhang, Roman Sobolewski, M Marso. Impact of thermal annealing on nonequilibrium carrier dynamics in single-crystal, freestanding GaAs mesostructures, Semiconductor Science and Technology, (04 2014): 0. doi: 10.1088/0268-1242/29/4/045022

TOTAL: 6

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

Number of Presentations: 0.00

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

Lucas Crandall (undergraduate) received the University of Rochester Donald M. Barnard Prize

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Yunus Akbas	0.65	
John Serafini	0.00	
Jie Xu	0.00	
Jing Gao	0.00	
Necdet Basaran	0.00	
Graham Jensen	0.00	
Fei Song	0.00	
Yong Wang	0.00	
FTE Equivalent:	**0.65**	
Total Number:	**8**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Anton Koroliov	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Roman Sobolewski	0.04	
Hui Wu	0.04	
FTE Equivalent:	**0.08**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Elizabeth Bradley	0.07	Electrical and Computer Engineering
Johua Berenson	0.00	Electrical and Computer Eng. and Physics
Han Zhang	0.00	Electrical and Computer Engineering
Lucas Crandall	0.00	Electrical and Computer Engineering
Arwa Elbeshbishi	0.00	Electrical and Computer Engineering
Andrew Stern	0.00	Electrical and Computer Engineering
Rabi Sherstha	0.00	Electrical and Computer Engineering
FTE Equivalent:	**0.07**	
Total Number:	**7**	

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: 7.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 7.00

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:...... 4.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 7.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 1.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 1.00

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: 0.00

Names of Personnel receiving masters degrees

NAME	
Grahan Jensen	
Fei Song	
Total Number:	**2**

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Arturas Jukna	0.03
FTE Equivalent:	**0.03**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment.

Technology Transfer

We established working collaboration with the group of Dr. Sudhir Trivedi <strivedi@brimrose.com> from the Brimrose Technology. They provide us for collaborative tests and characterization with the highest quality CdMnTe and CdMgTe single crystals for applications in sub-picosecond/THz-bandwidth transient generation and electro-optic detection. The crystals can also be used in our electro-optic sampling system as electrical-to-optical tranducers

FINAL REPORT

Terahertz (THz) technology offers an important range of potential applications within different domains, such as broadband communications, high resolution spectroscopy, radars, environment monitoring, biomedical testing, materials and device inspection, wireless networks, security, etc. As a consequence in this ARO project, our research we focused on several aspects of THz technology and spectroscopy.

Ballistic transistor development

As part of the joint, University of Rochester and University of Massachusetts, Lowell project, Rochester research has been focused on studies leading to a development of a novel room temperature THz amplifiers, based on developed by us ballistic deflection transistors (BDTs), as well as on time-domain characterization of BDTs, in order to experimentally demonstrate their THz frequency range operation.

For THz amplifier simulations, we have designed an 8-stage BDT traveling-wave amplifier with 15 BDTs in each stage. BDTs were interconnected with the 185-Ω characteristic impedance coplanar waveguide for both the gate and the drain lines. The length of each differential transmission line was 320 μm, feasible for an on-chip implementation. The actual BDT equivalent circuit parameters were derived based on experimental performance of a BDT transistor with the 430-nm-wide channel, including both capacitive and resistive parasitics. A large number of amplifying stages were needed to achieve a large enough (in our case 3 mS) total transconductance for the assumed total gain of 6 dB. Simulation results have demonstrated that our amplifier can achieve a 2.7-THz bandwidth with a gain flatness of ±0.3-dB. The return loss was better than –10 dB up to 2.5 THz and the gain-bandwidth product reached 10.8 THz. Although the device representation in our simulations had been based on low-frequency BDT parameters, our studies clearly demonstrated that BDT amplifiers had a high potential to achieve the THz-level performance. The latter observation has been independently supported by comprehensive Monte Carlo (MC) simulations. Finally, we stress that in the studied amplifier, its gain was limited by the transconductance of our present-day BDTs and we expect a dramatic improvement by introducing BDT nanostructures with the channel width below 200-nm.

For picosecond, time-domain (THz-bandwidth) characterization of our BDTs, we have designed and implemented, a special "experiment-on-chip" setup that, in general, enables of testing even ultrafast electronic devices. The system is driven by a mode-locked, femtosecond laser with the optical output (train of 100-fs-wide pulses with the repetition rate of 76 MHz) split into two, so-called, excitation and probe beams. The excitation beam is aimed at a photoconductive switch, incorporated in the coplanar waveguide structure. Through the photoconductive effect, the excitation beam launches into the transmission line a picosecond electrical transient that is, subsequently applied to the BDT gate, triggering the transistor output signal. The temporal shape of the drain signal is, in turn, sampled using an electro-optic (EO) transducer positioned at the close vicinity behind the BDT. As a reference, we also time resolve our electrical input transients by temporarily placing EO crystals just before the BDT. The actual, measured BDT output pulse had a ~230 GHz bandwidth, what is expected from an ~μm-size-channel of a BDT used in this experiment. In fact, it also agrees well with MC simulations for a ~800-nm-channel BDT. Based on our simulations, scaled-down BDT should achieve sub-ps performance.

Transient THz and pump-probe spectroscopy

As part of the program we have developed a completely new THz spectroscopy system and refined our existing optical pump-probe femtosecond spectroscopy setup. The THz system is now fully operational and we routinely get approx. 300-fs-wide electrical transients with the spectrum extending to 4 THz. The system consists of professional (from TeraVil, Vilnius, Lithuania) THz emitter and detector devices and their operation is based on the photoconductive effect in low-temperature–grown Gas crystals. Both the emitter and detector are excited by 100-fs-wide optical pulses generated by our self-mode–locked MIRA900F femtosecond laser. The system is placed inside an enclosure filled with dry nitrogen, in order to avoid THz absorption by water vapor. Besides THz spectroscopy that system can be used to characterized THz nanodevices.

Using our femtosecond optical pump-probe spectroscopy system, we have performed extensive time-resolved characterization of novel Si-on-glass nano-materials. Si-on-glass is an interesting material with possible applications ranging from ultrafast electronics to solar cells. We used our femtosecond pump-probe method for characterization of amorphous and microcrystalline silicon films grown on glass substrates. Depending on their growth process, the measured normalized transmissivity change ($\Delta T/T$) waveforms exhibited a bi-exponential carrier relaxation with the characteristic times varying from picoseconds to nanoseconds. The collected data, i.e., the family of $\Delta T/T$ transients, were interpreted using a three-rate–equation, electron trapping and recombination model. The solution of the rate-equation model, the time-dependent total concentration of excited carriers, fitted very well our experimental $\Delta T/T$ transients and we could identify that carrier trapping, followed by Shockley–Read–Hall recombination were the dominant relaxation mechanisms in our samples with the electron–phonon cooling being secondary. An excellent fit between the model and the experimental traces also obtained us to find a correlation between the Si film growth process, its hydrogen content, and the associated trap concentration. The observed relaxation dynamics in samples grown under different conditions reflected the trap-site densities and trapping lifetimes in the samples, providing much needed feedback to the control Si-on-glass growth conditions.

Ternary CdMgTe single crystals are among the most promising members of the partially substituted CdTe, II-VI class of materials and have very unique both photoconductive and electro-optic properties. These are very highly resistive semiconductors (resistivity $>10^8$ Ohm•cm) with a very short carrier decay time; thus, they are ideal for generation of intense, THz-bandwidth bursts of electromagnetic radiation. At the same time, these materials exhibit, as they parent CdTe and ZnTe crystals, a large Pockels effect, resulting in potential applications as ultrafast electro-optic modulators for optoelectronics. For photo-electronic applications, it is very important to understand the CdMgTe optical photoresponse and its dynamics, as well as the main relaxation channels of photoexcited carriers. With this aim in mind, we have performed femtosecond pump-probe spectroscopy studies of as-grown $Cd_{1-x}Mg_xTe$ single crystals with various concentrations of Mg atoms and measured nonequilibrium, time-resolved carrier dynamics. The obtained this way experimental information in the form of a family of $\Delta T/T$ waveforms was numerically analyzed using a set of differential rate equations. The approach has been similar to that used in the case of Si-on-glass samples described above and we observed that in CdMgTe carriers got photoexcited on femtosecond time scale through two mechanisms, standard valence band-conduction band excitation, and excitation into the conduction band of trapped electrons. It turned out that traps played the crucial role in CdMgTe photoresponse. After light illumination the photo-excited carriers were initially trapped with the trap-time of ~200 fs. Nonradiative electron-hole recombination was the secondary relaxation process with the recombination time of ~5 ps. Electron-phonon scattering was the least probable process and became relevant only for high intensity photon pumping. Overall, the photoresponse of as-grown CdMgTe crystals is on the order on ~10 ps with the sub-picosecond initial transient. The latter is a great feature for generation of THz transients for THz spectroscopy studies. On the other hand, the very large trap concentration, are not desired for, e.g., radiation detection applications, since it not only lowers carrier mobility, but ever further reduces the mobility-carrier–lifetime product – the figure of merit in radiation detectors. More studies on, e.g., annealed CdMgTe crystals are needed.

Asymmetric nanochannel devices

In the Year2, we have initiated our optical measurements of novel asymmetric nanochannel devices (ANCDs) obtained from our collaborators from the University of Salamanca, Salamanca, Spain. The devices were fabricated on an InGaAs/InAlAs quantum-well heterostructure grown onto an InP wafer. They consisted of 1.2-μm-long, ~200- to 300-nm-wide channels that were etched in an InGaAs/InAlAs quantum-well heterostructure with a two-dimensional electron gas (2DEG) layer. ANCDs, contrary to conventional diodes, do not rely on energy-barrier concepts to achieve rectification, but rather their nonlinear I–V characteristics result from the carrier transport in an asymmetric nano-channel. The ANCD planar geometry allows for a flexible design and easy integration as a multi-element sensor or with either optical nano-concentrators or THz coupling antennas. Based on Monte Carlo (MC) simulations, ANCDs are expected to be efficient THz generators and viable THz detectors. In ANCDs, carrier transport is confined to a 2DEG layer in order to take advantage of its ultrahigh mobility and in this way enhance the ballistic transport and minimize the carrier transient time. Depending on the device's dimensions and/or fabrication process and the level of its control, there are two basic types of ANCDs: "normally OFF" devices with a channel open/depleted at zero bias and "normally ON" devices, where the channel is always conducting. These two types exhibit quite different I–V curves.

Our focus of these preliminary studies has been on optical properties of ANCDs and we have demonstrated that the normally ON devices can be operated as very sensitive, single-photon–level, visible-light photodetectors. The ANCD I–V curves were collected by measuring the transport current both in the dark and under 800-nm-wavelength, continuous-wave–light laser illumination. In all of our devices, the impact of the light illumination was very clear, and there was a substantial photocurrent, even for incident optical power as low as 1 nW. The magnitude of the optical responsivity in ANCDs with the conducting nano-channel increased linearly with a decrease in optical power over many orders of magnitude, reaching a value of almost 10,000 A/W at 1-nW excitation. The physics of the photoresponse gain mechanism in the conducting channel (normally ON) ANCDs arises from a dramatic difference between a subpicosecond transient time of electrons travelling in the 2DEG nano-channel layer and the microsecond lifetime of holes, optically excited and, subsequently, pushed toward the substrate. We note that gain in our ANCDs is comparable to that of avalanche photo-diodes; thus, ANCDs should be practical photon counters, if their dark current can be controlled and sufficiently minimized.

Completed theses

Graham H. Jensen defended his Electrical and Computer Engineering MS Thesis entitled: “Temperature Dependent Femtosecond Pump Probe Spectroscopy of Thin Film Vanadium Dioxide” (2014).

Ms. Fei Song defended her Materials Science MS Thesis entitled: “Femtosecond Nonequilibrium Carrier Dynamics in CdMgTe Single Crystals” (2015).

Outreach

During the 2012 summer we were engaged in the very successful ARO HAS and URA Programs. The HSAP fellow was Logan Toops, a Junior from a local, Rochester-area high school. The URAP intern was Elizabeth Bradley, a Senior in the UR Department of Electrical and Computer Engineering. They were supervised by a mentor, Yunus Akbas, a graduate student supported by ARO.

During the course of the program, during the academic years, 5 students, Joshua Berenson, Elizabeth Bradley, Arwa Elbeshbishi, Lucas Crandall, and Andrew Stern, took for-credit Independent Research Courses (ECE391) under the supervision of Prof. Sobolewski and performed research related to the ARO project.

During the course of the program, during summers, 4 students (besides Elizabeth Bradley in 2012), Joshua Berenson, Han Zhang, Andrew Stern, and Rabi Sherstha spent entire summers working on ARO-related projects under the supervision of Prof. Sobolewski. They were supported by the UR Undergraduate Research Discover Program.