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Summary Report

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I spent the past year as a fourth-year graduate student at Princeton University under the supervision of Prof. Claire Gmachl. Our group's research focuses on developing mid-infrared light sources, and in particular quantum cascade (QC) lasers. QC lasers are semiconductor laser structures that are powerful emitters in the mid-infrared and terahertz wavelengths. Our lab group specifically focuses on mid-infrared QC lasers, of which there are multiple applications. Many of these applications involve trace gas sensing, or the detection of molecules at exquisitely small concentrations. With this capability, we enable research on and commercialization of such technological innovations as bio/chemical weapons detection, breath analysis for real-time medical diagnostics, broadly deployable environmental and hazardous emissions monitoring systems, and defense countermeasures.

My research encompasses improving the performance and expanding the capabilities of quantum cascade laser technology. The evolution of the field has led to some deep-rooted, foundational assumptions about QC structure design and fabrication that stem from "what worked" in the early development days. With new fabrication technologies and more advanced knowledge of the system physics, there are ripe opportunities to question some of these fundamental assumptions and challenge the status quo of device design and fabrication. In the process, we realize performance improvements and new device capabilities. My work habits make me most productive when I run multiple projects in parallel. Below, I summarize projects on which I have developed, made progress, and/or published over the previous year.

1) Excited state and 14.8 μm QC lasers for benzene detection: Achieving high performance from long wavelength mid-infrared QC lasers (that is, at wavelengths beyond 12 μm) is technologically difficult. However, many pressing applications in this longer-wavelength region motivate the development of such devices. Most all QC structures to date have used a conventional energy state configuration to create the radiative electron transitions, i.e., a first-excited state to ground state transition. Yet the QC architecture is remarkably amenable to new device design concepts. Seizing upon this creative freedom, we are investigating the use of optical transitions created from higher-lying energy states. We discovered that this technique can effectively increase the strength of the radiative electron transition, thereby increasing laser gain and lowering threshold currents. The technique can be especially effective for QC devices with operating wavelengths beyond 12 μm. Here, the extra boost to oscillator strength can help compensate for many of the impediments to longer-wavelength lasing, such as larger optical waveguide losses and the increasing difficulty of attaining electron population inversion.

2) Intersubband lasing from "hot" electrons high in k-space: As a direct result our research on excited state QC structures, we have observed lasing from electrons having large wave vectors high in k-space. The discovery is particularly exciting because

conventional wisdom holds that all the interesting physics happens at band edge extrema where charge carriers most easily accumulate—most generally near $k \approx 0$. In our particular device, we observed lasing from two energetically stacked optical transitions in each QC active region. When electrons enter the active region, they may experience our originally intended excited state transition. Alternately, they may non-radiatively scatter out of the upper energy state of the primary optical transition into a high k-space state. This creates a second optical transition which, in terms of charge carriers, is subordinate to the first. While the non-radiative scattering process is common to all QC lasers, the high k-space phenomenon present in our device owes to the extra lower-lying energy states that are by default built into our excited state structure. Interestingly, our models fail to accurately predict the strength of this high k-space optical transition. Instead, we must increase the transition strength to replicate the observed behavior. This discovery could eventually lead to device design strategies and applications where we intentionally inject electrons into high k-space states.

3) Short injector QC lasers for high power and efficient mid-infrared light: A DARPA funded project, the goal is to ideally optimize QC laser performance. In another example of reexamining foundational assumptions, we take a fresh look at the role of each element in a QC laser stage. QC laser active cores are typically made from multiple periods of alternating active regions and injector regions; in particular, the active regions are where the radiative transition is engineered, and the injector regions provide several functions necessary to electronically connect each successive active region. These injector regions tend to consume a substantial part of the optical mode, even though they do not themselves contribute to photon generation. They also present extra "space" that electrons must traverse before the electrons are able to make another optical transition. We pose the question of whether we can accomplish the same key injector region functions while significantly decreasing the injector length. The result could yield substantial increases in optical output power and conversion efficiency, as well as commensurate decreases in threshold current. Work on this project is ongoing, and will develop in the coming year.

4) Semiconductor-oxide heterostructures: While the design of the QC structure is one aspect of the field that has become tired, so too have the materials used to create QC devices. Because of their fabrication ease, telecom materials have naturally become the workhorse material for QC lasers. Yet, absent from the prescribed QC emitter construction is the required usage of any individual material system. Rather, there exist four more general requirements for any practical QC implementation:

(1) two materials with sufficient band edge offset to support optical transitions;
(2) a method for engineering population inversion between upper and lower energy states of the optical transition;
(3) at least one of the two materials must be dopable with charge carriers for the intended transport band; and
(4) the materials must be feasibly fabricated.

Freed from the conventional III-V semiconductor materials, we are investigating the use of alternate materials systems. For example, we have recently developed a strategy to fabricate a semiconductor-oxide QC structure. The work is in a preliminary stage, but should we be successful, the extremely large band offsets provided by insulator-semiconductor heterostructure interfaces could lead to completely new intersubband devices. In our immediate QC laser application, successful fabrication of a these devices could generate laser emission well below 4 μm, the end-goal of our initial research in this area.

5) II-VI quantum cascade structures: Taking the new materials concept a step further, we abandon the conventional III-V materials system entirely. Instead, we use a mix of II-VI semiconductors, namely ZnCdSe and ZnCdMgSe, to build QC structures. Advantageously, this semiconductor combination can be fabricated using standard molecular beam epitaxy technology. It has a much larger effective conduction band offset than what is found in III-V materials, which allows for higher photon energy QC designs having shorter wavelength emission. In our first attempt with this material system, we designed a conventional two-well active region QC structure with intended emission near 4.4 μm. Initial work focused on generating electrically pumped intersubband optical emission. Indeed, we have observed such electroluminescence in a device emitting at 4.8 μm, in relatively excellent agreement with the designed structure. We have thus proven that all of the fundamental elements required to create a II-VI QC laser are now in place. Current research focuses on device design strategies such as superlattice QC structures that mitigate small variations in material layer deposition thicknesses, along with showing lasing from a II-VI QC structure. This II-VI system is another example of a material amenable to light generation at wavelengths below 4 μm.

6) Mid-infrared photonic integration: Photonic integrated circuits—the interconnection of multiple optical components on a single semiconductor chip—have largely enabled today's advanced telecommunications capabilities and infrastructure. This technology was necessarily developed for wavelengths in the near-infrared (telecom) around 1.3 and 1.55 μm. Our mid-infrared QC lasers in fact use the same technological platform as telecom diode lasers. This conveniently lets us build on the work done in the near-infrared, and we are developing technologies by which some of the same on-chip light shuttling mechanisms and active and passive functional capabilities might be done for mid-infrared light. One ultimate application of our work is to develop a photonic integrated system for on-chip molecular sensing in the liquid phase. Our initial work has been on developing the ability to transition light from an active QC laser source into a passive waveguide. Here, the passive waveguide serves as interface for our mid-infrared light to evanescently interact with a target liquid sample.

7) QC laser modeling and software development: QC lasers are complex semiconductor heterostructures that are designed and engineered to meet very specific emission and performance requirements. They are, moreover, synthetic, man-made materials, in that we "trick" the material into doing something it wouldn't otherwise want to do. The engineering design work is thus of critical importance to producing a device processing the intended capabilities. I have written a software package, called *ErwinJr*, that rapidly and accurately models our coupled quantum well heterosturctures, enabling QC laser development. *ErwinJr* is now the software used exclusively by our research group to design lasers. Most importantly, with this software we have made significant

improvements in design accuracy: we now have a predictive accuracy that exceeds 99.5% between designed and fabricated QC structures. The software is also fast and user-friendly. We have, in fact, turned QC laser design into a "video game," in that undergraduate and high school students can experiment with and design advanced semiconductor heterostructures as summer research projects.

Over the past year, I have also undertaken other activities beyond my several research projects. Three colleagues and I are now over a year into a start-up venture focused on the commercialization of quantum cascade laser technology and much of our research at Princeton. Officially, Primis Technologies LLC became a company this past November. Primis Tech is currently in discussion with multiple Fortune 1000 companies under signed NDA. We are also in active discussion with several different government agencies coming to the sensing and security applications all from different angles.

I continue to be involved in several science outreach activities. Since 2003, I have been involved with the National Science Bowl program sponsored by the U.S. Department of Energy. My participation started by serving as a science judge and moderator for regional competitions, both middle school and high school. My involvement has increased over the years, and I have most recently assisted as a question author for the national competitions; I am now a moderator and science judge for the national competitions as well. Another notable outreach activity is my recent appointment to a term as chapter chair of the Princeton/Central New Jersey IEEE LEOS Section. The chapter had been dormant for several years, but has now been re-established with our first event held in April. My leadership team and I have planned a full list of activities and seminars for the coming year.