Opto-Electronic Characterization of Narrow Band Gap Semiconductors at Cryogenic Temperatures

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Introduction:

Semiconductors are fundamental to modern technology, with uses ranging from scientific research to commercial applications in computing and telecommunications. There is a great deal of interest in studying these materials, both to improve their use in current technologies and to discover potential future applications in novel devices.

In this work, we focused on a characterization apparatus used for studying semiconductors (see Figure 1). This apparatus optically probed a semiconductor sample with a 532 nm Nd:YAG solid-state laser and used a monochromator and detector to generate the sample's photoluminescence (PL) spectrum. This spectrum can then be used to determine the material's band gap, an important physical property. In addition, the band gap's temperature dependence can be investigated by placing the sample in a 10 K cryostat.

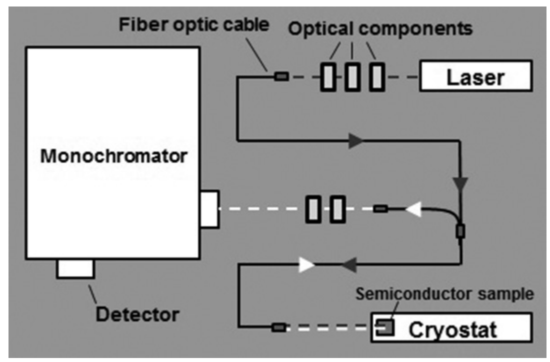

Figure 1: Characterization apparatus diagram. Laser light shown in gray, photoluminescence in white.

The characterization apparatus was formerly only capable of optically probing semiconductors that photoluminesce visible to near infrared light. Major modifications were made to this apparatus to add to its functionality so that it could: (1) employ electrical measurements in addition to optical probing, and (2) detect narrow band gap semiconductors, which photoluminesce with mid to far infrared light. These modifications entailed both redesigning existing parts of the apparatus using the CAD software SolidWorks and incorporating new components into the setup.

Modifications:

The limitations of the apparatus were narrowed down to three major areas: the optical components, the cryostat, and the monochromator. Modifications were made to these areas to overcome their respective limitations.

The optical components were not positioned optimally, resulting in a low signal to noise ratio. This was corrected by repositioning each component individually until the signal was maximized. There was also an issue with noise from the laser; although the laser nominally lases at 532 nm, it is a frequency doubled laser that has significant lasing at 1064 nm as well. It also has significant emissions at several wavelengths near 532 nm. These two issues were resolved with the addition of two new filters, one to block light at 1064 nm and one to block light near 532 nm while still transmitting 532 nm light.

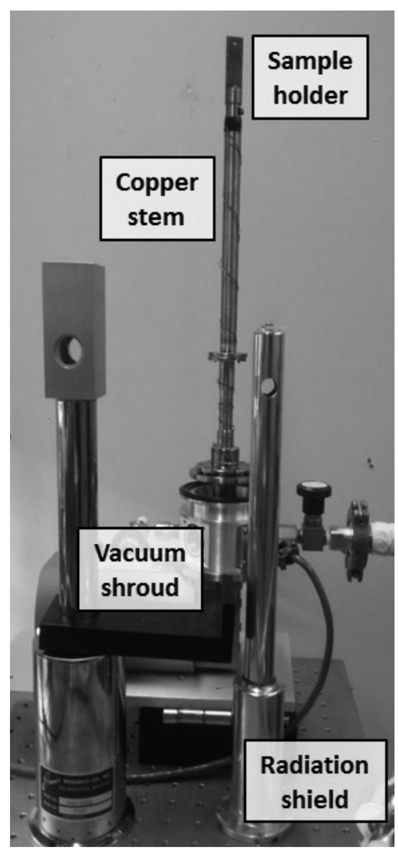

Figure 2: The former cryostat, disassembled. Labeled components were modified.

The cryostat (see Figure 2) had several distinct limitations to consider. For one, it took up to two hours to cool down from room temperature

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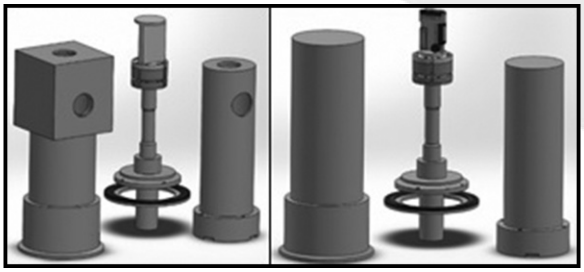

Figure 3: SolidWorks models of both versions of the new cryostat components, optical (left) and electrical (right).

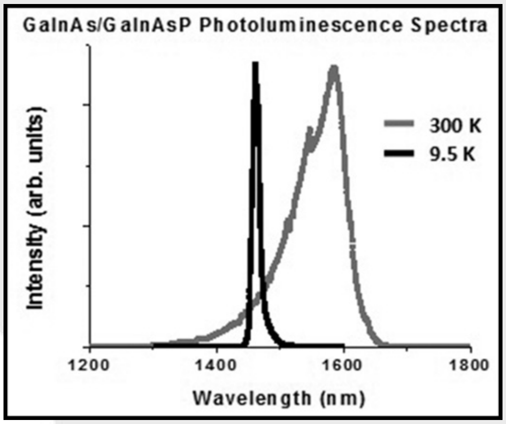

Figure 4: Photoluminescence spectra for GaInAs/GaInAsP sample at 300 K (room temperature) and at 9.5 K.

to 10 K. The cryostat vacuum shroud windows absorbed mid to far infrared light, which prevented detection of the photoluminescence of narrow band gap semiconductors. The sample holder did not allow for wiring of the sample, a necessity for making electrical measurements. The modifications needed to overcome these problems yielded two sets of new cryostat components, an optical version and an electrical version (see Figure 3).

Both versions have a much shorter copper stem. This reduces cooling time since the sample holder is cooled by contact with this stem, which is in turn cooled by contact with the cryostat. The optical version has a vacuum shroud and radiation shield that accommodate new CaF_2 windows, which transmit visible to far infrared light (0.2-8 μm) and can therefore be used for narrow band gap semiconductor PL studies (i.e., InAs, InSb). The electrical version has a sample holder that supports the addition of 16 pin DIP sockets, which can be wired for electrical measurements. The electrical version also has a windowless vacuum shroud and radiation shield, which can be used when studying samples whose electrical properties are affected by ambient light.

There were four detectors that could be used with the monochromator. Two of them, an InGaAs detector and a photomultiplier tube, could be mounted onto the monochromator but could only detect light with wavelengths up to 1.8 μm, below the mid to far infrared regime. The other two detectors, InAs and HgCdTe, could detect mid to far infrared (up to 3.8 μm and up to 12 μm, respectively), but were not designed to be mounted onto the monochromator. Therefore, mounting plates were made for properly positioning the InAs and HgCdTe detectors on the monochromator where light would be focused on the detectors.

Testing:

Preliminary tests on the completed modifications suggest they are fully functional. In particular, photoluminescence spectra of a GaInAs/GaInAsP sample (see Figure 4) exhibited well-defined peaks both at room temperature and at 9.5 K in the cryostat, indicating that the optical alignment and new filters were yielding a satisfactory signal to noise ratio for making measurements. The signal was also clear enough to observe the peak being narrower and shifted to a smaller wavelength for the 9.5 K spectrum, an expected occurrence that shows the temperature dependence of band gap.

Future Work:

Most of the modifications have been completed and have undergone initial testing with promising results. The electrical sample holder still has to be wired for electrical measurements and the fiber optic cable will need to be replaced as it only transmits up to a wavelength of 2.5 μm. This limits the operating range of the upgraded setup, as all the modified parts function at wavelengths up to 8 μm. Further testing is required when all parts are complete and the functionality of the apparatus can be assessed as a whole.

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