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Modification of band gap and spin-orbit coupling in type-II GaAs/AlGaInP heterostructures through biaxial strain modulation

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Abstract:

Gallium Arsenide (GaAs) and Aluminum Gallium Indium Phosphide (AlGaInP) heterostructures have been investigated for optoelectronic devices. Recently, they have also attracted new interests for spintronics applications. Here, we want to present our results in exploring the concept of strain modification of band gap and spin-orbit coupling in these material systems. For this purpose, a PZT piezoelectric actuator is used. Numerous bonding agents and curing methods were tested and we were able to identify one suitable for accurately transferring applied strain while maintaining its reliability over 300K-4.2K thermal cycles. Strain measurements were taken on the order of 10^{-5}, which provided a dynamic ΔL range up to $1.05 \times 10^{-3} mm$. At 4.2K, we also verified that the applied biaxial strain with variable time intervals yielded predictable and repeatable results. Furthermore, results on band gap modification through strain engineering will be presented by using low temperature photoluminescence measurements.

Introduction:

The current goal is to show that the band gap of p-type GaAs and AlGaInP could be manipulated and regulated by a synchronized application of strain. It has been shown that the energy band gap shifts as a function of strain due to lattice mismatch in $Ga_xIn_{1-x}P$ at room temperature; at strains of <0.05% the change in band-gap energy <2.5meV.[1] For our experiment strain was induced using a PZT-layer piezoelectric actuator; it deforms homogenously in the z-direction (figure 2) generating a reduction of area on the mounting faces and thus producing a strain. Samples of p-type GaAs quantum well and AlGaInP were thinned down between 35 - 50μm and mounted to the piezo. Photoluminescence testing was then executed at room, liquid nitrogen, and liquid helium temperatures since changes in gap energy are more apparent at lower temperatures. Our initial expectations were subdued by the realization that our piezo was not able to deliver enough strain to our samples; however, we were still able to prove that the band gap does change with strain.

Procedure:

- The piezo actuator used in this experiment was a $PbZrTiO_3$ (PZT) on-stack-insulation (osi) piezo actuator[3] having a ceramic cross-section of 7x7mm and an active length of 9mm (figure 1).

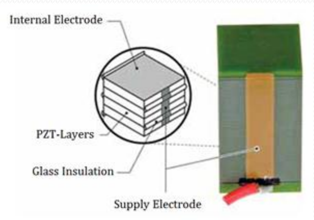


Figure 1

- In order to quantify the piezo deformation, the piezo was calibrated using a 90° Tee Rosette strain gage[4] (figure 3).

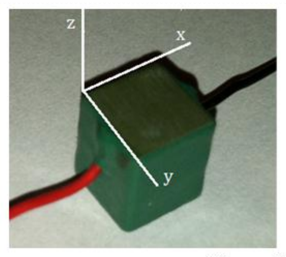


Figure 2

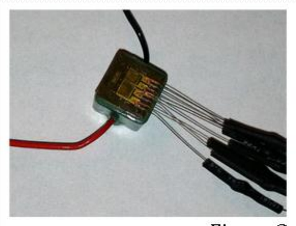


Figure 3

- A two-part epoxy[5] was used to bond the strain gage to the surface of the piezo (figure 3); a mixing ratio of 1:1 was to produce a harder bond to ensure an accurate transfer of strain.

$$\varepsilon = \frac{(\Delta R)}{R_o}\left(\frac{1}{GF}\right)$$

ε = strain

R_o = initial resistance of gage

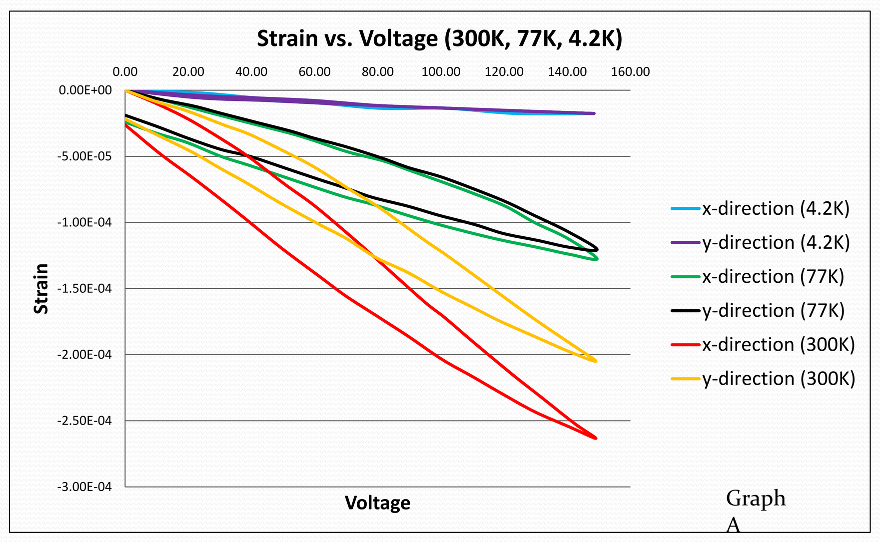
ΔR = change in local resistance

GF = Gage Factor

Equation 1

- Gage factors of 1.667 and 1.467 were used for 77K and 4.2K respectively (equation 1).
- At lower temperatures the strain measurements were time-dependent and consideration for reaching a thermal equilibrium between piezo, epoxy and strain gage must be accounted for.

- @ 300K strain in the x-direction measured -2.63×10^{-4} and in the y-direction it measured -2.05×10^{-4}.
- @ 77K strain in the x-direction measured -1.28×10^{-4} and in the y-direction it measured -1.21×10^{-4}.
- @ 4.2K strain in the x-direction and y-direction both measured -1.76×10^{-5}.
- It has been shown that at temperatures above 4.2K the PZT-actuators exhibit hysteresis when cycling through voltages;[2] our testing verified this (graph A).
- At lower temperatures the deformation of the piezo appeared to become more homogenous.



Graph A

- Processing of the samples was accomplished by way of a lapper, thinning them to <50μm.
- The same two-part epoxy was used to directly transfer the sample from the chuck of the lapper to the piezo.
- The bonding process was given 24hrs at which time the assembly was placed in a solution of acetone until the sample could be easily removed.
- Figures 4 and 5 show setup for strain gage calibration and photoluminescence testing.

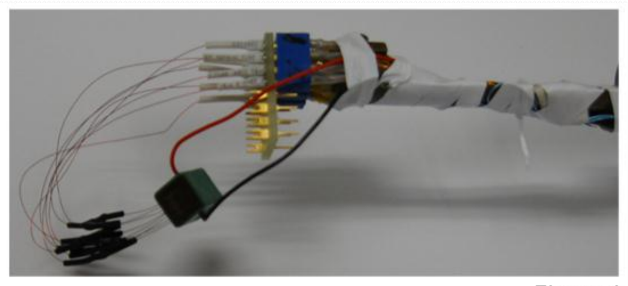


Figure 4

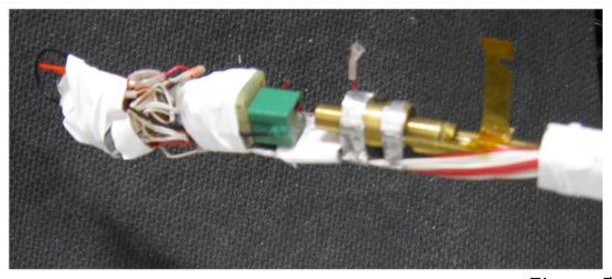


Figure 5

- The linear coefficient of thermal expansion (CTE) for the endfest epoxy is $90 \times 10^{-6}(°C)^{-1}$
- The CTE for GaAs is $5.9 \times 10^{-6}(°C)^{-1}$.[6]
- From similar data[6] the CTE for AlGaInP is on the order of $2 \times 10^{-6}(°C)^{-1} \rightarrow 14 \times 10^{-6}(°C)^{-1}$.
- The epoxy has a CTE that is over ten times that of the samples and can thus be inferred that at cryogenic temperatures the volume of the epoxy will have an acute reduction in volume compared to that of the two samples
- The strain produced by the epoxy due to temperature reduction from 300K to 4.2K can be estimated (using equation 2) to be -2.3×10^{-2}; this strain well exceeds that of which is produced by the piezo.

$$\frac{l_f - l_o}{l_o} = \alpha_l(T_f - T_o)$$

l_f = final length

l_o = initial length

α_l = CTE

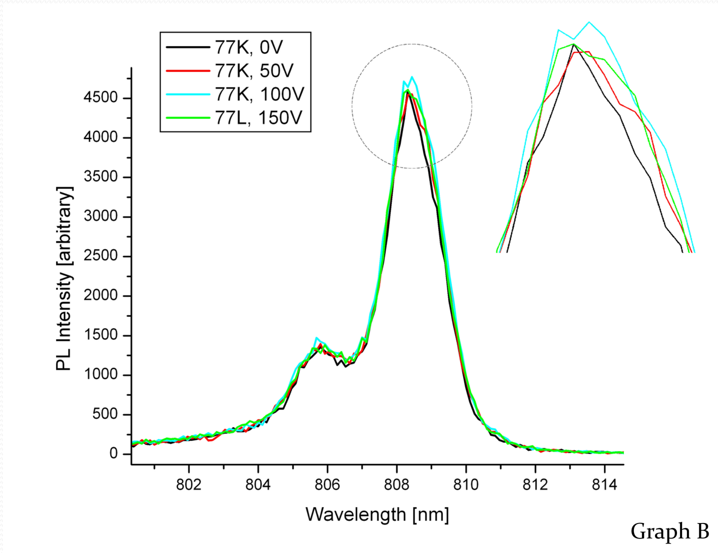
T_f = final temperature

T_o = initial temperature

Equation 2

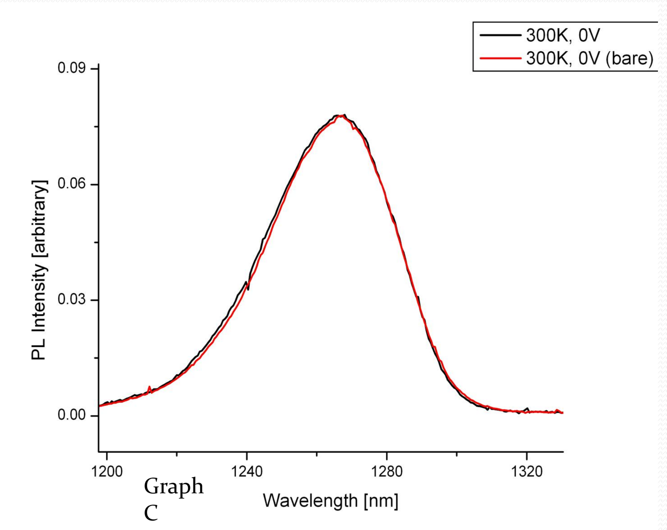
Results:

- Graph B shows the photoluminescence data for the p-type GaAs quantum well at 77K for different piezo voltages.
- The voltage was stepped up at a rate of 10V every 5 minutes; an energy gap shift could not be inferred from the data (graph B).



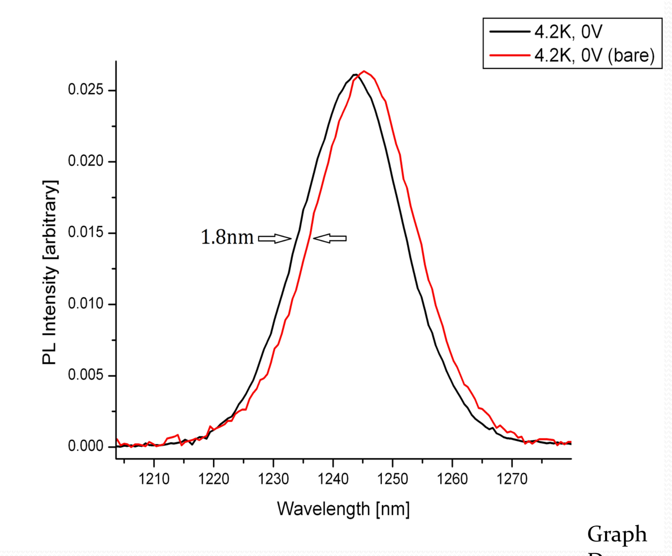
Graph B

- For the AlGaInP sample, the results were also inconclusive at all three temperatures
- A comparison was examined between the processed sample (thinned, polished and glued) and the unprocessed/bare sample.
- @ 300K and 77K, there was no evident change (graph C).



Graph C

- When the AlGaInP was brought to 4.2 K, the processed sample (black curve) showed a blue shift of 1.8nm (graph D) measured at the half-width.
- Varying the voltage disclosed no differences, so it can be assumed that the strain was not a result of the piezo.
- Our presumption is that the difference in the CTE of the epoxy and the sample led to a contraction of the epoxy that was far greater than that of the sample, producing a compressive strain on the sample.



Graph D

Conclusion:

Initially the goal of the experiment was to be able to dynamically control the band gap of p-type GaAs and AlGaInP from strain produced from a piezoelectric actuator. The data was inconclusive since there was no evident change in the gap energy. When processed and unprocessed samples of AlGaInP were compared, there was a measurable shift in the wavelength. It was assumed that this shift was a result of differences in the thermal expansion of materials. Future testing must be done to determine if strain was indeed responsible for the shift; this would require a new method of generating more strain on the order of what is produced from the contraction of the epoxy.

Possibilities for further progression in experiment:

- A different bonding agent could be used to possibly make a thinner bond for more accurate strain transfer and also be less affected by temperature fluctuations.
- There is a concern from the manufacturer of the piezo about the effect of acetone on the contacts of the piezo, should there be any crack in the polymer coating; possibly find a different glue for use with the lapper.
- In order to ensure proper placement of the sample onto the piezo, a fitting could be machined to house the piezo and the lapper chuck during the bonding process.
- During processing, a smoother finishing on the sample could produce a more accurate transfer of strain.
- A more mechanically driven method to produce strain may work better; for instance pushing on the middle of the back of the sample while the edges are held in place would cause a deformation and strain.
- Uniaxial strain could be studied through the usage of an IPMC (ionic polymer/metal composites), which bends with applied voltage; essentially a sample mounted on either side could have a linear compressive or tensile strain.
- Further processing of the sample; thin the sample more so that less strain would have a greater effect on the sample.
- Perform low-magneto transport experiment and explore any correlation with strain and spin-orbit coupling.

References:

1) Hiromitsu Asai and Kunishige Oe. *Energy bandgap shift with elastic strain in $Ga_xIn_{1-x}P$ epitaxial layers on (001) GaAs substrates.* Journal of Applied Physics, 54, 2052 (1983); doi: 10.1063/1.332252.

2) M. Shayegan, K. Kari, Y.P. Shkolnikov, K. Vakili, E.P. De Poortere, and S. Manus. *Low-temperature, in situ, uniaxial stress measurements in semiconductors using a piezoelectric actuator*, Applied Physics Letters, Volume 83, Number 25. December 22, 2003.

3) Part No. Pst 150/7x7/7, from Piezomechanik. Munich, Germany.

4) Part No. WK-00-062TT-350, from Vishay Micro-Measurements. Raleigh, North Carolina.

5) Part No. 45640 "plus endfest 300" from UHU. Buehl, Germany.

6) William D. Callister Jr. and David G. Rethwisch. *Fundamentals of Materials Science and Engineering, an Integrated Approach.* John Wiley and Sons, Inc. 2008. 3rd. ed. (pg. 706, 817).

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