# Compound Semiconductors: Illinois Contributions and Perspective

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**Abstract**

This paper describes some of the contributions that the faculty and students of the University of Illinois have made to the field of compound semiconductors over the last half century.

## INTRODUCTION

The invention of the transistor by John Bardeen and his colleagues at Bell Laboratories in 1947 catapulted the study of semiconductor materials and devices to the forefront of research endeavors which has continued till today and will continue into the foreseeable future. Advances made in the research domain have been translated into the commercial domain and their impact could not have been predicted by the inventors of the transistors! Broadly speaking, the materials called semiconductors have changed the course of the world and the welfare of humanity. Every aspect of the human endeavor is dominated by products and processes enabled by semiconductor materials and devices with wide ranging technical and economic impact. It is hard to envisage world economy without semiconductor technology; it is the bedrock of the electronic and information age. Its overall impact can be best left to historians and others to gauge.

The era of semiconductor research began in earnest at the University of Illinois in 1951 with the arrival of Professor John Bardeen (Nobel Laureate, 1956 and 1972) from Bell Laboratories; while active research in compound semiconductor materials and devices commenced with the arrival of N. Holonyak, Jr. in 1963 having developed the GaAsP visible laser and light emitting diodes at the General Electric Laboratory in Syracuse [1]. Professor Holonyak, Jr was the first student of John Bardeen at Illinois! With this beginning, there have been many significant contributions emanating from Illinois in compound semiconductors over the years but it should be said that they began with these pioneers. Illustrious names in the field that have been faculty members at Illinois over the years include B. Streetman, G. Stillman, K. Hess, H. Morkoc, J. Coleman, J. P. Leburton, M. Feng, K. Choquette, and others. In addition, illustrious names in the field who were students at Illinois include R. D. Dupuis, D. Dapkus, J. Campbell, G. Craford and many others. It is hard to fully capture all the contributions and names of all the contributors in a short paper; therefore, only some will be highlighted here.

## LASERS

With the strong experience in optical devices and materials growth that N. Holonyak, Jr. [1] brought from GE, it is not difficult to imagine that he and his students started making rapid advances in the laser field. His group made and continues to make strong contributions to the development of quantum well lasers in different types of III-V heterostructures [2,3]. They were the earliest group to demonstrate these devices in materials grown using liquid phase epitaxy (LPE -- InGaAsP) and metal-organic chemical vapor deposition (MOCVD – AlGaAs/GaAs). Holonyak and his group developed various unique processing methods to realize efficient lasers. These methods include impurity-induced disordering [4] and compound semiconductor native oxide growth [5]. Both of these methods were utilized for carrier confinement. Professor Coleman and his students made significant contributions to the development of reliable and commercial viable strained layer InGaAs quantum-well lasers [6]. These are widely used as pump lasers for rare-earth doped optical fiber amplifiers. Fundamental work by Professor K. Hess and his group was critical to developing the first program, MINILASE, for simulating lasers based on first principles [7]. Recent work on lasers has focused on novel types of devices such as patterned quantum dot lasers by Coleman et al. [8] and vertical cavity surface emitting lasers (VCSELs) by Choquette et al.

[9]. Figure 1 shows patterned InGaAs/GaAs dots obtained using electron beam lithography patterning and MOCVD. Professor J. Leburton who joined Illinois in 1981 has contributed extensively to the understanding of carrier dynamics in quantum dots through simulation based on realistic models [10].

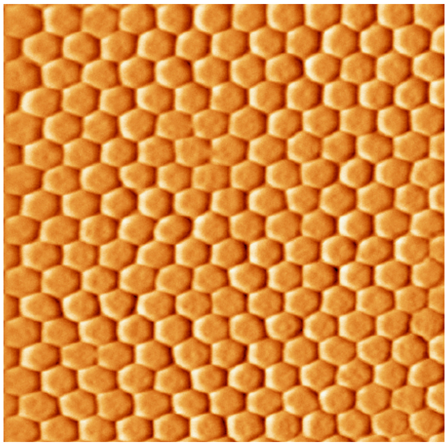

**Figure 1** Micrograph of patterned InGaAs/GaAs quantum dots. Each dot is less than 100 nm wide.

## MATERIALS

Excellent materials are critical to the realization of excellent devices. Diffusion or doping during growth were common methods of introducing impurities into semiconductors prior to the emergence of ion implantation. Professor Streetman who joined the faculty at Illinois in 1966 worked assiduously to show that ion implantation could be applied to III-V compound semiconductors [11] and could be used for devices. Professor Stillman joined the faculty in 1975 and worked on fundamental materials issues involving both ultrapure high electron mobility materials and effects of high intentional levels of doping on band properties of III-V materials and impact ionization in these materials [12]. The knowledge derived from these research investigations lead to elegant work on the realization of high gain avalanche photodiodes. Later, his work on carbon doping became important in the realization of reliable heterojunction bipolar transistors (HBTs) [13].

## TRANSISTORS

Several transistor types ranging from metal semiconductor field effect transistors (MESFETs) to modulation-doped field effect transistors (MODFETs) and heterojunction bipolar transistors (HBTs) have been investigated in various III-V material systems. One of the earliest molecular beam epitaxy system in an academic institution was operated by H. Morkoc and his group and were able to grow and demonstrate high performance pseudomorphic AlGaAs/InGaAs/GaAs MODFETs [14]. This was one of the earliest demonstrations that strained layers could be utilized for practical devices. Pseudomorphic MODFETs have since found extensive applications in power and low noise amplifiers in various systems environments. High performance MODFETs or high electron mobility transistors (HEMTs) have also been achieved in AlGaN/GaN materials by Morkoc et al. and Adesida et al. [15, 16]. Professor Milton Feng and his group through systematic scaling principles coupled with band engineering have been able to achieve high speed performance for HBTs of over 700 GHz with the potential promise of THz operation [17]. Figure 2 shows a scanning electron micrograph of a fabricated pseudomorphic InP/InGaAs HBT; the emitter width was 0.25 μm.

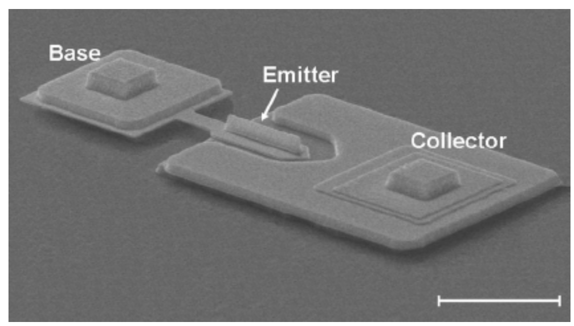


**Figure 2** Micrograph of pseudomorphic InP/InGaAs HBT.

Recent collaborative work by Feng and Holonyak Jr. have yielded a novel type of device -- the light emitting transistor (LET) [18]. This is a device which combines the operation of HBT and optical device in the base region of the HBT. Extensive work is currently being performed to elucidate the physical principles of this device; however laser action has been demonstrated [19] and it has been shown that LET devices can be achieved in various heterostructure materials ranging from AlGaAs/GaAs to GaN/InGaN. High level carrier transport using full-band Monte Carlo methods developed by K. Hess and Professor U. Ravaioli are used world-wide for advanced device simulations particularly for HEMTs and MESFETs [20]

## TRENDS AND PERSPECTIVE

It is quite certain that work in III-Vs will continue strongly both at Illinois and around the world. It may yet find applications as a partner to silicon in the post-Si digital era. Advancements in quantum dot and quantum wire growth and fabrication will result in new types of devices that perhaps have not been imagined at present [21, 22]. An example of a new direction in the growth of III-V nanotubes and nanowires is illustrated in Fig. 3. This is the work by Professor Xiuling Li [21] which utilizes strained planar bilayers released from a substrate to form III-V nanotubes.

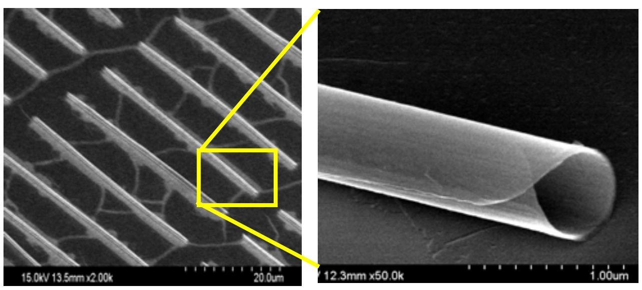


**Figure 3** Self-rolled compound semiconductor nanotubes.

These strain-induced self-rolling semiconductor nanotubes can find applications in various fields such as nanofluidics. Another novel avenue of application is enabled by heterogenous integration of III-V materials on flexible substrates as demonstrated by J. Rogers et al. [23].

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