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## InP—Into the Future

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**NASA**

## Indium phosphide - into the future

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### ABSTRACT

Major industry interest is beginning to be devoted to indium phosphide and its potential applications. Key to these applications are high speed and radiation tolerance; however the high cost of indium phosphide may be an inhibitor to progress. The broad applicability of indium phosphide to many devices will be discussed with an emphasis on photovoltaics. Major attention is devoted to radiation tolerance and means of reducing costs of devices. Some of the approaches applicable to solar cells may also be relevant to other devices. The intent is to display the impact of visionary leadership in the field and to enable new directions and broad applicability of indium phosphide.

### 1. INTRODUCTION

I would like to start out with a story about football - I will relate it to indium phosphide in a little while but it makes an important point. Back in 1957 when I graduated from the University of Oklahoma, we played football for fun. Bud Wilkinson's teams were awesome. In the first quarter the first string would play with the adversaries; in the second quarter, the second string. The third string played the third quarter and by the fourth quarter, practically anyone could play. I got spoiled by this - I thought scores were supposed to be 66-0. As we know, however, all good things must end. In the fall of 1957 (after I had graduated), Notre Dame came down and put an end to the longest winning streak in college football. The score was not high - something like 13-0. They did it very simply by concentrating on stopping four or five key plays that their intelligence indicated OU used when the going got tough. From there on it was simply execution. There is a message in there for us and I will come back to it later.

Next I would like to discuss leadership, because leadership is the key factor that underpins success. Leadership embodies many of the things I want to talk about today - it is a key word for all of us here. The first ingredient in leadership is vision - where do each of you want to be in 5 or 10 years; where do you want the technology of indium phosphide (InP) to be? The second step in leadership is to develop an action plan for achieving that vision. What key steps do we have to take to get there? Finally, in the course of implementing the action plan you have to perform and in our business that usually means innovative technical advances.

Let's talk about vision. What is your vision of what InP devices can become? What market niche can they fill? How can they change the course of human events? Hold onto that thought - but do not believe you are going to become wealthy doing it! That may happen but it is a byproduct of vision, action, and superior technology. If you are in this business to merely become wealthy, forget it! However, with 200 people attending a conference on InP, I know there is a tremendous vision as well as a tremendous opportunity provided we can bring it all together in a unified vision to focus our energies leading toward action plans.

Figure 1 depicts some of the present applications for InP. Each of you has an interest in one or more of these areas. The question marks cover all those that may have been inadvertently omitted or future applications that may spring out of this or other similar meetings. While all these areas are technically challenging, which may be the most successful? While prognostication is beyond the scope of this paper, the first step is to examine the special material characteristics of InP, then seek to capitalize on them to create a market niche.

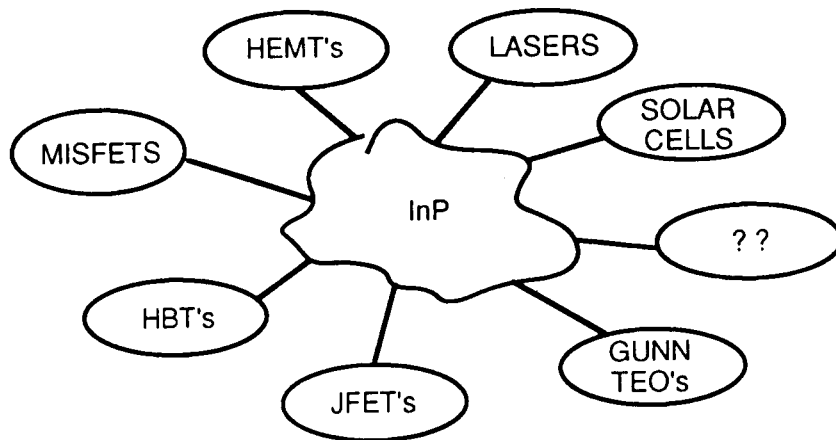


Figure 1. - Indium phosphide applications.

Figure 2 shows a selected list of special capabilities or characteristics of InP that I feel are important. I apologize if some major points were omitted, but I have highlighted several key areas that I feel are particularly

- HIGH SPEED \*
- RADIATION TOLERANT \*
- HIGH COST (BAD!)
- OPTOCHEMICAL ETCHING
- HIGHER FREQUENCY
- BETTER THERMAL CONDUCTIVITY
- GREATER BREAKDOWN FIELD

**\* REAL WINNERS**

Figure 2. - Special capabilities and characteristics of InP relative to GaAs and most other materials.

important and give InP a decided advantage. The first key characteristic is high speed and that is already being capitalized upon with devices reaching the one-hundred plus gigahertz range. There is a significant opportunity for growth in this area. The second key capability is radiation tolerance, and I will be more specific later. I feel radiation tolerance is the biggest sleeper and the biggest potential for market share in indium phosphide right now. High cost is bad to me, even though it may appeal to many (suppliers included)! Because I am in space power, we need a lot of area to change sunlight into electricity with solar cells. Indium phosphide can yield around 200 W/m<sup>2</sup> or so in space, and with applications spanning from 5 to 10 kW to about 100 kW, areal cost becomes an issue. When you are selling chips that are a few square millimeters, cost is an entirely different issue! Optochemical etching will be discussed briefly as InP has some unusual properties in that area that may not have been exploited sufficiently. The remaining three attributes are better left for detailed technical discussions rather than in this paper - you all are doing an excellent job in these areas.

Now, what about radiation tolerance? I believe this area offers substantial new horizons for InP when the devices are likely to be exposed to radiation such as electrons, protons, neutrons, gamma and x-rays, etc. Figure 3 summarizes some observations about radiation damage. From the very limited data available, it appears that HBTs, HEMTs, MISFETs, and solar cells all have at least twofold greater resistance to radiation than do comparable GaAs devices. Specifically, solar cells have

- ELECTRONS, PROTONS, NEUTRONS, GAMMAS, X-RAYS, ETC.
- HBT's, HEMT's, MISFETS, SOLAR CELLS ---
  - 2 TO 10X BETTER THAN GaAs
  - VERY LIMITED DATA
- SOLAR CELLS ANNEAL EASILY
  - LIGHT
  - CURRENT
  - TEMPERATURE
- WHAT DOES THIS IMPLY FOR ACTIVE CIRCUITS?
  - NEED DATA

**INP BECOMING RECOGNIZED AS OBVIOUS MATERIAL  
OF CHOICE IN HEAVY RADIATION ENVIRONMENTS**

Figure 3. - Radiation tolerance considerations.

tenfold greater resistance to electrons and protons than do GaAs solar cells. This is all the more amazing when you realize that solar cells are minority carrier devices whose performance is strongly influenced by the minority carrier diffusion

length. Furthermore, InP solar cells anneal easily - illumination during radiation promotes substantial annealing - about a further doubling in resistance. Finally, raising the temperature to about 100 °C totally anneals the damage. What, then, does this imply for irradiation of active circuits? Is anyone doing irradiation testing of fully operating InP devices at temperature? I would strongly recommend such testing. For example, NASA needs power management electronics capable of handling hundreds of volts in the strong neutron and gamma radiation environment of SP-100, the 100 kW space nuclear reactor power system. Conventional silicon transistors will not do this job and nonsemiconductor approaches are too heavy and unreliable. I firmly believe the InP will soon be widely recognized as the obvious material of choice for use in heavy radiation environments.

Let's look at a comparison of solar cells in radiation environments. Figure 4 compares silicon, gallium arsenide, and indium phosphide solar cells in various natural radiation environments near Earth. State-of-the-art production efficiency in silicon is 15 to 16 percent, in GaAs 17 to 18 percent, and in InP about 16 to 17 percent - not greatly different. However, when these cells go into radiation environments we see large differences. For example after 10 years in geosynchronous Earth

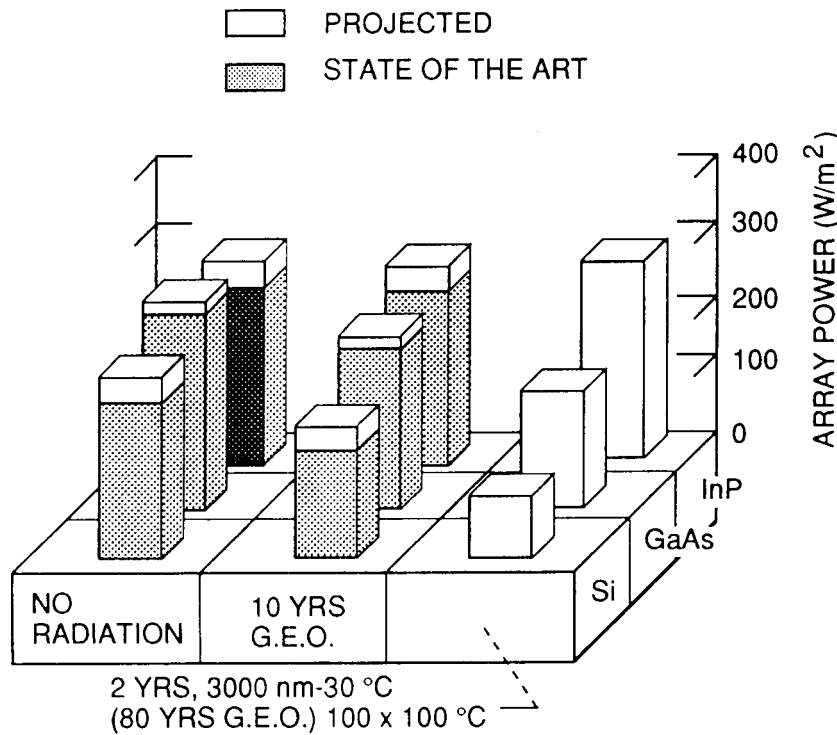


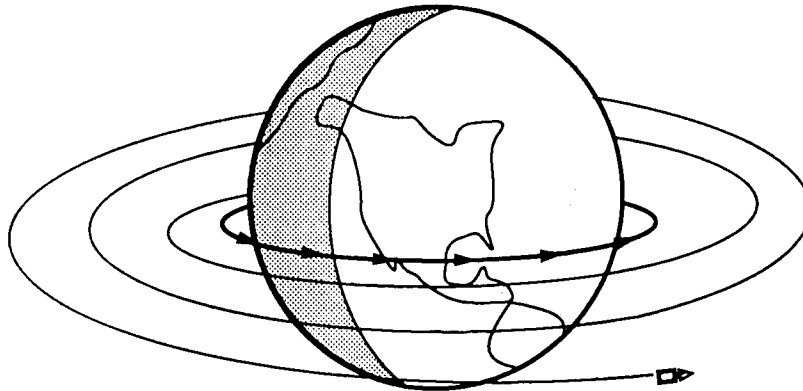
Figure 4. - Solar cell performance comparison.

orbit (GEO), silicon has lost about 25 percent of its power, GaAs about 10 to 15 percent, and InP, nothing. In fact InP in this application will yield about 50 percent more power after 10 years than an equivalent area of silicon. A more extreme case is an orbit at 3000 nmi, the heart of the Van Allen radiation belt. Two years here is equivalent to 80 years at GEO. Eighty years may sound long - and it is, but NASA is beginning to explore the technology for satellites with 30-year life so this is not out of line. In this application we envision using sunlight concentrators to

reduce the cost of InP solar arrays plus boosting the temperature to 100 °C at 100X sunlight concentration. In this case, InP still does not lose any performance while both GaAs and Si have dropped dramatically. Now InP produces three times more output than silicon and about 50 percent more than gallium arsenide. Another paper at this conference by Irving Weinberg will detail the results of solar cell testing on the Naval Research Laboratory's LIPS III space test. These space tests appear to be confirming the radiation tolerance of InP. What does this kind of performance mean to NASA? Well for one thing, as shown in Fig. 5, it suggests that InP solar cells in lightweight refractive sunlight concentrators could power a "space tug" propelled by electric thrusters through the radiation belts to deliver cargo to orbit beyond Earth. Because power levels from hundreds of kilowatts to megawatts are required for short trip times, cost, area, efficiency and radiation tolerance are key issues. InP solar cells in sunlight concentrating systems fill the bill nicely. Without InP, nuclear power systems would be the sole choice.

ISSUES:

- LOW MASS
- RADIATION TOLERANCE
- HIGH EFFICIENCY



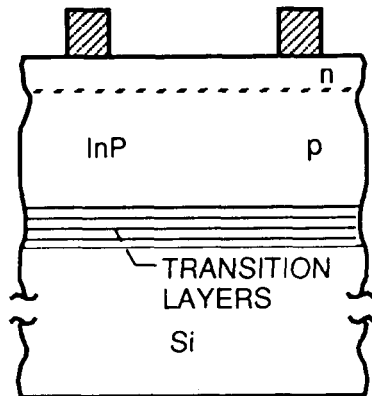
SUGGESTED PV SYSTEM:

- InP REFRACTIVE CONCENTRATOR ARRAY

InP CONCENTRATOR ARRAY POTENTIALLY  
RADIATION HARD, LIGHTEST WEIGHT OPTION  
AMONG ALL POWER SYSTEMS

Figure 5. - Photovoltaic powered Orbit Transfer Vehicle.

What about cost reductions? Sunlight concentrators are one way to reduce the cost of InP photovoltaic systems because lenses or mirrors are much cheaper than InP (or any other semiconductor as far as that goes). I would like to find a way to substantially reduce the cost of InP solar cells regardless of application, however efficiency must not be sacrificed. Figure 6 shows one approach that challenges the state-of-the-art of semiconductor processing. This figure suggests trying to solve the 7 percent lattice mismatch between silicon and InP by using carefully graded and annealed transition layers. The silicon base would provide much increased strength and handleability, reduced mass, and much reduced cost. A corollary benefit is increased InP material availability because only about a 5 μm thickness is needed for



- BENEFITS

- INCREASED STRENGTH
- REDUCED WEIGHT
- REDUCED COST •
- INCREASED MATERIAL AVAILABILITY

- ISSUES

- LATTICE CONSTANT, EXP. COEFF. MISMATCH
- DISLOCATIONS
- COUNTERDOPING BY Si DIFFUSION

- SOLUTIONS

- GRADED TRANSITION LAYERS
- REDUCED PROCESSING TEMP.

- UNIQUE TO PHOTOVOLTAICS?

Figure 6. - Indium phosphide solar cells on silicon.

total light absorption. Clearly the technical issues here are very challenging and will require some of the world's best minds to solve. Great strides have been made in epitaxial growth of GaAs on Si with a 4 percent lattice mismatch by using tailored transition layers, superlattice structures, and careful annealing to kill mismatch generated dislocations. Virtually bulk GaAs properties are being produced in such combinations. With InP, we are stretching nearly a factor of 2 more in mismatch. The payoff for success is substantial and significant however, because it will open up space to using a lot of InP - and in fact, may open the door to numerous terrestrial applications.

For example, let me stretch your thinking. Were we to succeed in growing high quality InP on silicon, and knowing how to already grow quality GaAs layers, might it be possible to someday consider a super-hybrid circuit compound of all three materials? Conceptually, one could then have a chip with devices from several different materials, each using the characteristic of that material to advantage to provide a circuit that exceeds the capability of all three (or more) materials. Of course there are immensely difficult processing issues that are beyond our knowledge to solve today but that should not stop us from dreaming. I want to stimulate your thinking and challenge you to attack these "next generation" problems as well as solving the formidable problems we are struggling with today. It is better to attack the hard problems - even if you do not fully succeed, for your progress is much greater than it would have been were only more modest problems addressed.

Let's address another way to achieve light weight. Weight is important to NASA because lifting mass to low Earth orbit is an expensive proposition today. For example, sending 1 kg of mass to orbit at an altitude of 150 nmi costs about \$8000. At that rate, a round-trip ticket for a person would cost about \$600,000! A far cry from your airline ticket. By the way, putting the same 1 kg of mass on Mars costs around \$500,000, so it is pretty obvious why NASA has an interest in reducing mass of systems. The Space Station Freedom solar arrays use silicon solar cells, produce about 100 to 150 W/m<sup>2</sup> with a specific power of 66 W/kg. Figure 7 shows a NASA goal of reaching 200 W/m<sup>2</sup> and 300 W/kg - a factor of 5 improvement for the solar array specific power. Such achievement would yield large benefits to spacecraft in terms

- ULTRALIGHTWEIGHT, LONG LIVED ARRAYS
  - GOAL: 200 W/m<sup>2</sup>, 300 W/kg
  - SOA: 100 W/m<sup>2</sup>, 66 W/kg
- CLEFT OR PEELED FILM
  - LASER PROCESSING
- ISSUES
  - HANDLING AND INTERCONNECTS
  - ARRAY ASSEMBLY
  - DEVICE EFFICIENCY
- OTHER DEVICES

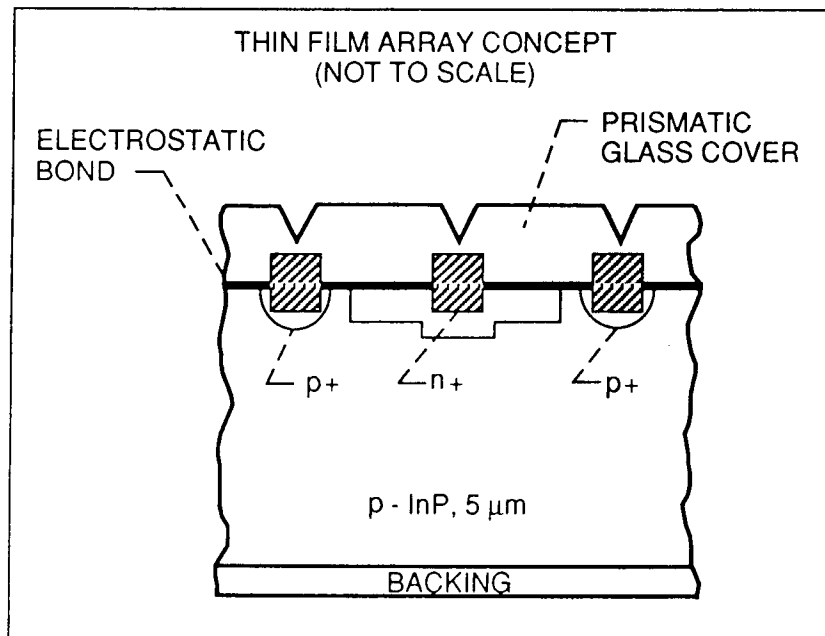


Figure 7. - Thin-film InP cells for lightweight arrays.



of increased pay load and reduced costs. We believe these goals may be attainable with InP. The inset shows a 5  $\mu\text{m}$  thick InP solar cell made using a number of processes such as the CLEFT process developed by Kopin Corp. or the peeled-film approach pioneered by Carnegie-Mellon University. High quality films have been produced by these approaches, albeit little attention has been devoted to InP. There are a number of special ideas represented in this cell. First, grooves are opened by laser processing the film. Next  $p^+$  and  $n^+$  heavy diffusions are made into these wells to form junctions and then the surface  $n^+$  (or  $p^+$ ) broad area junction is formed by a lighter diffusion. The cell now has a series of interdigitated  $n^+$  and  $p^+$  junctions. The contact metallization is deposited into the laser grooves and built up flush with the surface. This now looks much like a transistor structure. To protect the cell, and to make array interconnections, we make a special cover glass. Once again the metallization is placed in grooves, only now the pattern includes the patterns necessary to interconnect all the cells into an array and bring the power to a user. Light can be directed around the grid lines by making prisms in the surface to refract the light around the metal and into the active semiconductor. The surface of a cell covered with such a prismatic cover shows no evidence of metal grid lines, thus the light is virtually totally absorbed in the semiconductor and able to produce useful power. The cell can be bonded to the cover glass by electrostatic bonding which requires no adhesive. Thus, the cell is hermetically sealed, the metal grid lines are also bonded so a complete interconnected array can be made in one step. Adding a rugged backing completes the array. Concepts like this can lead beyond the 300 W/kg array.

Now let me challenge you to another aspect of this ultrathin material. Is it feasible to make active devices such as transistors using the back and front of the device instead of using only the single surface? Does availability of the third dimension into the bulk lead to new or innovative device structures that may be advantageous?

Finally, let me briefly mention optochemical etching of InP. By exposing InP to light in a chemical bath, it is possible to make lenses on the surface, grooves or other reasonably complex geometries. How might this surface modification opportunity lead to new devices - can these be used as part of an integrated optics system? How can this peculiar characteristic of InP be used to produce new devices or functionally integrated circuits? I will leave that to your ingenuity for the next InP conference.

Let me simply end up where I started. All of you at this conference have a vision; you see the applications - but do you have an action plan on where you (and we the InP community) want to be in 10 years? Will InP become the material of choice for many applications - for example in radiation environments? Where are the niche markets - how can we utilize the things we have learned in working with III-Vs, a veritable candy store of options? We have the opportunity to attack and surmount critical, challenging barriers and deliver the new technologies that will change the course of human events. All we need is leadership and vision. Like Notre Dame and OU . . . Notre Dame had leadership with the vision, they had their action plan and they executed. Just as they won a great victory, we too can win a great victory and deliver new, superior InP technology for the world's benefit.



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