SILICON RESEARCH AND TECHNOLOGY

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The mood of the silicon R&T Workshop was not one of optimism this year in contrast to that of the 1980 workshop. The cause(s) of this depression may have been: (1) the inability of the silicon community to fulfill the optimism of the last meeting which foresaw an 18 percent silicon cell; (2) the present emphasis on increased radiation hardening [e.g., 15 percent efficiency end-of-life (EOL) after $10^{15}/cm^2$ 1 MeV electrons] which did not seem feasible; or (3) the pressure from GaAs work with its potential for higher BOL and EOL power output.

In spite of the failure to date to achieve an 18 percent efficient silicon solar cell (AMO at 25° C), there are presently indications that the goal is approachable. The best results are open circuit voltages in excess of 690 mV in an MINP structure. Other work has pointed to surface recombination velocity (SRV) as the limiting factor (in diffused cells) and possible ways of bypassing this problem. Evidence that indicates a reduction in the predicted bandgap narrowing (resulting from heavy doping) and an increase in the Auger lifetime in heavily doped silicon is also encouraging for further improvements in diffused junction silicon solar cells.

Optimism for success in overcoming the present problems, without immediately encountering further problems in an already highly optimized device, was muted. However, since major voltage gains were a result of new technology (for the diffused silicon group), infusion from other fields might make another major improvement. Techniques borrowed from other solid state devices could be keys to a further increase in silicon solar cell efficiency. Such improvements could complement or supplement the boost in voltage achieved by the MINP cell which is an outgrowth of MIS technology. Such modified or hybrid silicon cells could provide the benefits of silicon technology with much higher initial output. Again, enthusiasm for such improvements was dampened by the recognition that perhaps none of these improvements would survive a radiation environment. Only after we were reminded that many satellites do not fly in the radiation belts and others need more power early in a mission was the cloud over BOL efficiency improvements lifted somewhat.

Hybrid structures using GaP, ASi (amorphous silicon) or some other such wide bandgap semiconductor on the silicon surfaces could provide a "window" to lower the SRV for both the front and the back of a silicon cell. This could overcome the problems observed in forming an effective p^+ back contact on 0.1 Ω-cm material. The use of electrostatic bonding and perhaps ion implantation into the cover glass was proposed as a possible way of forming an MINP cell which is less sensitive to radiation than presently predicted.

Other areas of potential cell improvement included: (1) Ingot material modification, where the Air Force program for altered doping (Ga vs. B), ultrahigh purity FZ, and cold crucible techniques were mentioned; (2) processing changes, to take advantage of surface gettering and to prevent defect generation; (3) counter doping, the introduction of internal getters or compensation for radiation damage; and (4) use of n-type rather than p-type substrates and/or processing modifications have been shown to improve BOL performance. The material modification or counter doping is expected to improve EOL performance, but no encouraging data are yet available.

Some useful tools in studying SRV of emitter surfaces have been tried or suggested. Electrostatic charge applied to the AR coating of a completed cell is perhaps the simplest means of testing the effectiveness of surface passivation and/or n+ (or p+) surface layers. More quantitative methods would include special structures which can use C-V techniques on heavily doped surfaces and voltage applied to water drops on isolated surface areas. An idea that might have interest as a test structure or as a future solar cell would be an FET cell, where the gate would be a thin tin oxide conductive layer for application of voltage between the grids. An integrated circuit cell could provide self-biasing for this structure which could improve radiation hardening over a trapped charge structure.

A final question addressed the user's preference of a commercially produced 20 percent GaAs cell vs. a commercially produced 18 percent Si cell, assuming equal costs and weight. The most important answer to this question was a sobering declaration that, despite obvious advantages of the GaAs cells, the most important difference would be flight experience and many inferior systems fly and will continue to fly until requirements force a change.

A short congress of the Silicon R&T, the Radiation Damage, and the Blanket Technology Workshops was most useful in emphasizing the basic conservatism of project offices in general and their reluctance to change unless forced to do so. Nevertheless, diversity in cell characteristics was encouraged; particularly if sufficient test or flight data become available to allow clear and comfortable choices to be made for specific missions.

The participants in the Silicon R&T Workshop were

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Stan Solomon	Spire
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ADVANCED DEVICES

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The working group on Advanced Devices addressed five questions:

1. Has sufficient progress been made to warrant confidence that the 30 percent efficiency at 100x and 80° C goal can be achieved? If so, what are the most promising approaches; if not, how should the program be altered?

2. What approaches seem likely to achieve efficiency beyond 30 percent? What barrier problems ought to be attacked?

3. What cascade cell manufacturing problems do you envision?

4. What approaches are most likely to succeed for interconnecting a cascade cell stack?

5. How can we overcome the requirement for lattice constant matching in monolithic cascade cells? Is the direct bandgap requirement too stringent?

The working group obtained the following responses to these questions:

1. Has sufficient progress been made toward the 30 percent goal?

In general, substantial progress has been made and there is no reason to change the goal at this time. The metal interconnected cascade cell reported at this conference demonstrated considerable improvement in both cell area and efficiency over the state-of-the-art 1 year ago. Progress is being made in both materials and processes required to achieve the goal.

The question of minimum efficiency was also addressed. For a new technology to be accepted, it must show some advantage over the existing technology. Cascade cells should exhibit about 3 percentage points of efficiency above that of GaAs to justify their consideration as a replacement, with all else being equal.

As cascade cells become a proven technology, questions about their application need to be addressed. Among these, three emerged as most important:

(1) Radiation effects need to be considered, especially in series connected cascades, where degredation in one cell's short circuit current affects of the stack's short circuit current.

(2) Laboratory evaluation procedures and standards must be developed. In many cases, these cells will require new test procedures.

(3) To reach the 30 percent goal, we will use concentration. More work is needed to evaluate what concentrator designs are most appropriate for high efficiency cascade cells. Specifically, what concentration and concentrator design are appropriate for various potential missions?

2. What approaches are likely to exceed 30 percent efficiency, and what barrier problems must be addressed

The main barrier problem with existing technology is the photovoltaic effect itself, and higher efficiency technologies probably will not be photovoltaic, at least as we see it today. We really do not know what these future technologies are. Use of surface plasmon effects was one idea reported at this meeting. For very high power, in the megawatt range, nuclear might be preferable, assuming political and safety problems do not stand in the way.

This question is very difficult for a group of experts in photovoltaics to address. We recommend that future SPRAT conferences invite input from nonphotovoltaic technologies to encourage us to think innovatively.

3. What cascade cell manufacturing problems are envisioned

This question was somewhat difficult to address, because the devices to manufacture have not themselves been defined. Manufacturing engineers are very innovative and have tackled difficult semiconductor devices in the past (such as 64K RAMs), so that concern about manufacturability is not warranted at this time.

Some discussion centered on epitaxial growth technology. OM-VPE and LPE have been used, and both are funded technologies. OM-VPE has been used to make the best working device to date and is a versatile and reproducible technique. LPE has been used to make large area, multilayer devices in the laser and LED industries and is also being used to make good GaAs solar cells. As a general statement, if the attractive cascade cell has more than five or six layers, some or all of which require close thicknes control, then OM-VPE will be the preferred technology.

4. What approaches seem most likely to succeed for interconnecting a cascade cell stack

Five techniques for making cascade cell stacks were mentioned, two of which form series interconnects and three of which leave open the option of either forming a series interconnect or addressing cells individually. The latter might be worth a further consideration if the reduced process yields or lessens radiation hardness. The techniques are

MIC^2 (metal Interconnect). - This has been used to make the best monolithic cascade cells to date. It is also a useful diagnostic tool since it allows addressing of individual cells. This feature allows its use in a nonseries-connected configuration. Its drawback is added processing.

Tunnel junction. - This has been demonstrated with LPE growth over small areas. Because the cells do not require extra processing after growth, it would be attractive, but only if reproducible low resistance, large area tunnel junctions are feasible. As the 30 percent cell will require three junctions, and tunnel junctions are hard to achieve in high gap materials, it is possible that a future cell will be a MIC^2-tunnel junction hybrid, with the top interconnect MIC^2 and the bottom tunnel junction.

Ge interconnect layer. - Possibly, a thin layer of Ge placed between the two cells will provide a good shorting junction. This is especially attractive in the GaAs-AlGaAs system, where Ge is lattice matched.

Mechanically bonded stack. - It is possible to mechanically bond two individual cells together. Such a configuration provides the option for individual addressing of cells. This could circumvent various interconnect and materials growth problems.

Spectrum splitting using, for example, dichroic filters. - This eliminates the interconnect problems at the price of a more complex mechanical system, and the cost of additional components such as the filter.

All of these approaches are being examined, and it is not possible to recommend a preferred one at this time.

5. How can we overcome the requirement for lattice constant matching in monolithic cascade cells? Is the direct bandgap requirement too stringent?

The lattice matching requirement has evolved from many years of experience in crystal growth. While it is a general rule, there are some exceptions, such as Ge on Si and possibly GaAsP on GaAs. Thus, while lattice matching is important to bear in mind, processes and cell designs should not be rejected a priori because they violate lattice matching requirements. Spectrum splitting and mechanically stacked structures do not require lattice matching.

Indirect gap materials are usable for both the top and bottom cells. Because the top cell is grown epitaxially, it must be relatively thin. One way to use an indirect gap material there is to use the spill-through current match technique, in which above-gap light passes through to the bottom cell, bearing in mind that even indirect materials collect blue light in a relatively short length. The bottom cell can use the bulk of the substrate, and can be an indirect material as well.

In summary the group's observations and recommendations were as follows:

1. Cascade cell development is progressing toward the 30 percent goal. A minimum efficiency advantage of 3 percent is required to ensure use in competition with the next best existing technology, all else being equal. Radiation effects and concentrator designs need to be considered more carefully. Laboratory procedures and standards must be developed.

2. We must encourage innovation to identify next generation high efficiency technologies. Future SPRAT conferences should include inputs from nonphotovoltaic technologies to encourage this innovative thinking.

3. Manufacturing problems are not envisioned at this time, because the cascade cell is not well defined. LPE and OM-VPE epitaxial technologies are being developed. If the best cell requires a relatively complex epitaxial structure, OM-VPE will probably be preferred.

4. A number of interconnect approaches are possible and are being investigated. Those that do not require series connection may be useful if the series connection significantly reduces process yield or radiation hardness.

5. Lattice constant matching is not always required. Indirect gap materials may be used for both the top and bottom cells.

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