PASSIVATING WINDOW/FIRST LAYER AR COATING
FOR SPACE SOLAR CELLS

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ABSTRACT

Chemically grown oxides, if well designed, offer excellent surface passivation of the emitter surface of space solar cells and can be used as effective passivating window/first layer AR coating.

In this paper, we demonstrate the effectiveness of using a simple room temperature wet chemical technique to grow cost effective passivating layers on solar cell front surfaces after the front grid metallization step. These passivating layers can be grown both on planar and porous surfaces. Our results show that these oxide layers: (i) can effectively passivate the front surface, (ii) can serve as an effective optical window/first layer AR coating, (iii) are chemically, thermally and UV stable, and (iv) have the potential of improving the BOL and especially the EOL efficiency of space solar cells. The potential of using this concept to simplify the III-V based space cell heterostructures while increasing their BOL and EOL efficiency is also discussed.

INTRODUCTION

For space solar cells light- and radiation-induced effects are known to adversely affect the solar cell performance. An important degradation mechanism is known to be the generation of fast surface states at the emitter/first layer antireflective (AR) coating interface. It is a common practice to use physical vapor deposition to deposit the AR coating. For simple solar cell structures (e.g. Si and InP-based homojunction cell structures), the layers of the AR coating are deposited directly onto the emitter surface. This approach is known to destroy the stoichiometry of the emitter layer. It introduces additional defects at the emitter/AR coating interface. Physical vapor deposition of the AR coating is also known to adversely affect the performance of TPV cells.

The application of theoretical and experimental advances in the physics of semiconductor heterostructures to space solar cells has resulted in the fabrication of the large variety of high efficiency heterostructure space solar cells known today. However, increasing the number of layers of the heterojunction cells may have a negative impact not only on cost but on the functionality of these cells under the space radiation environment. This is especially true for cells designed for high radiation orbits. Simply put, the more
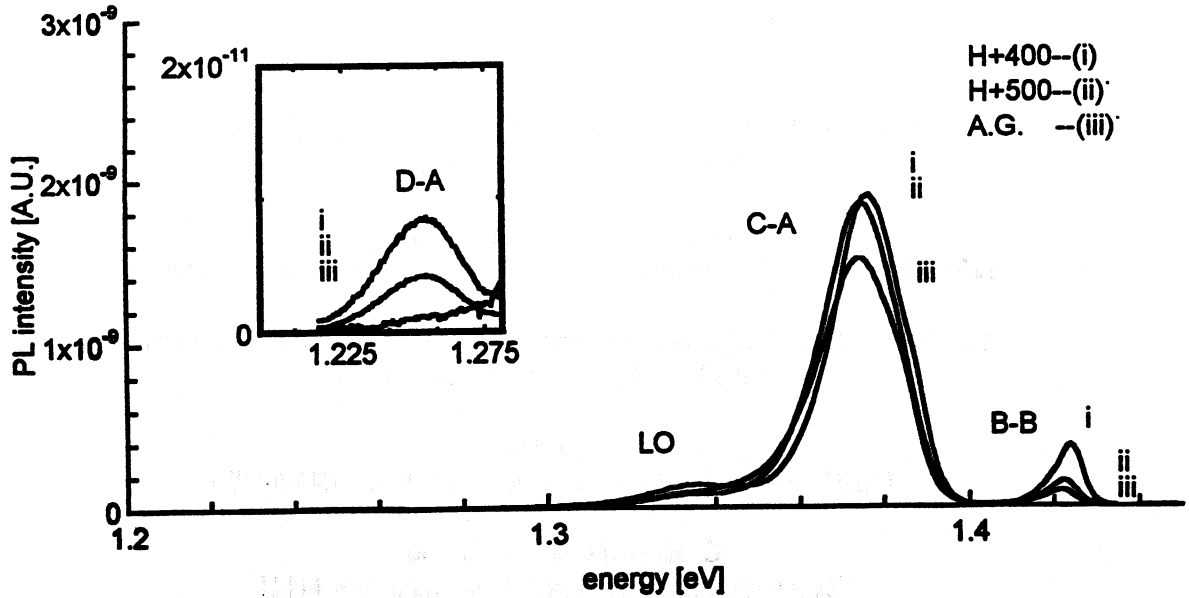
Figure 5. Photoluminescence spectra of homoepitaxial p⁺n InP solar cells structures
that were hydrogenated for 2 hours and then annealed at the indicated temperatures.
An as-grown PL spectrum is shown for comparison and the inset indicates the
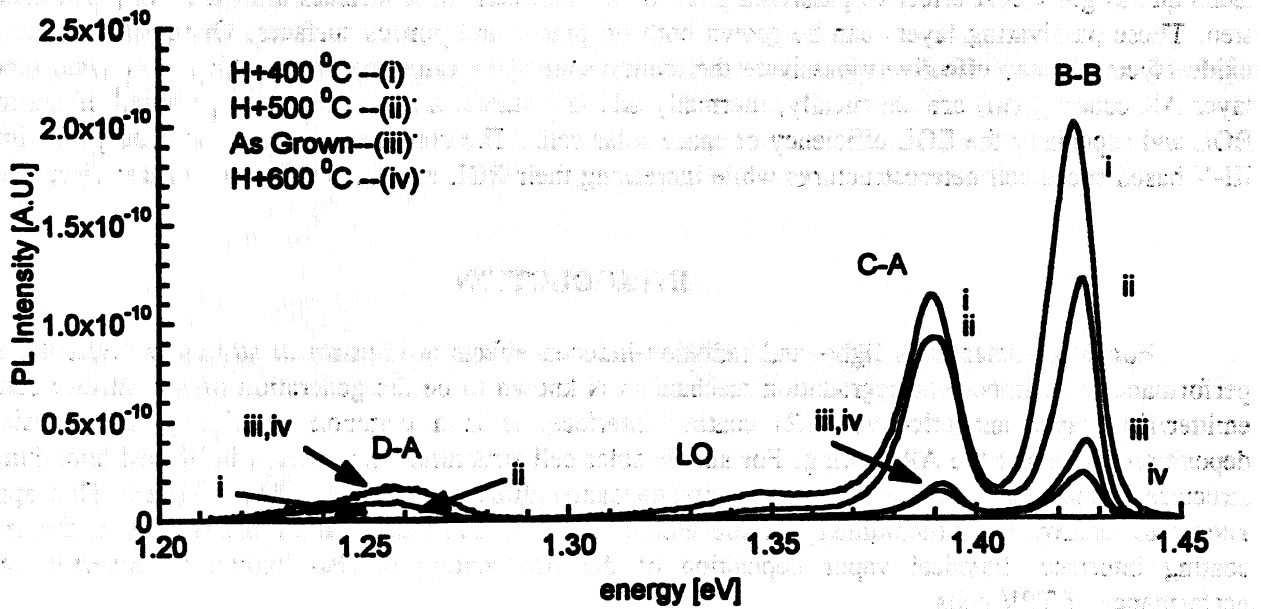presence of a very small D-A peak.

Figure 6. Photoluminescence spectra of heteroepitaxial p⁺n InP solar cells structures
that were hydrogenated for 2 hours and then annealed at the indicated temperatures.
An as-grown PL spectrum is shown for comparison. Note that the D-A peak is clearly
pronounced in this case.

layers these heterostructure cells have, the larger the chance of degradation under the space environment. Therefore, it is highly desirable to reduce the number of layers of heterostructure space solar cells, as for example, by eliminating the passive window layer.

High efficiency III-V based space solar cells often use a window layer grown on the surface of the emitter prior to depositing the layers of the AR coating. This window layer partially passivates the emitter front surface and reduces the surface recombination velocity at the surface, thereby improving the cell performance. Although current epitaxial growth techniques (e.g. MOCVD, MBE) are capable of producing abrupt, atomically sharp heterojunction interfaces, lattice matched window layers (e.g. AlGaAs, InAlP, GaInP$_2$ and AlInP$_2$) grown by epitaxy, increase the cost and reduce the yield of finished cells. Based on the results presented in this paper, we suggest that replacing the presently used window layers with stable, ultrawide bandgap, chemically grown oxide layers can decrease the fabrication cost and increase the yield of space solar cells, while increasing both the BOL and EOL efficiencies.

Chemical oxides grown by a simple, yet reproducible wet chemical growth technique, which are of interest for replacing the above window layers, have ultrawide bandgap, e.g. 6.8 eV for In(PO$_3$)$_3$ grown on InP [1]. These oxides are transparent in the useful region of the spectra, and bandgap values larger than 5 eV should help to minimize the Fermi-level pinning effect and the oxide/semiconductor interface electrical instability.

One of the early criticisms about chemically grown oxides, still very much widespread within the semiconductor device community, is that they are thermally and electrically unstable [2]. Based on our published data on oxides grown on InP [e.g. 3-11] and preliminary unpublished data (oxides grown on Si, Ge, and GaAs), part of which are summarized in this paper, we are confident that through a relatively short R&D effort these oxides can be stabilized for any space solar cell. Using this approach, record high V_{oc} and J_{sc} values have been measured under AM0, 25°C conditions at NASA LeRC at 890 mV for a diffused junction p$^+$n InP cell and at 55.5 mA/cm^2 for a diffused junction n$^+$pp$^+$ Ge cell, respectively.

RESULTS AND DISCUSSION

InP Solar Cells

While developing the technology of the low cost fabrication of high efficiency, radiation resistant thermally diffused p$^+$n InP solar cells at NASA-LeRC/CSU, using chemically grown In(PO$_3$)$_3$-rich oxide for surface passivation and as a first layer AR coating, we have been able to consistently and reproducibly obtain world record high open circuit voltage (V_{oc}) values of 885 to 890 mV (AM0, 25 °C measured at NASA LeRC). We showed that the origin of the instability of chemically grown oxides on InP surfaces was the presence of In-rich oxide layer on the top of the P-rich In(PO$_3$)$_3$ interfacial oxide layer.

The fact that these thermally diffused cells had larger V_{oc} values than those of any other InP solar cells, including cells made by epitaxial techniques, proves that if the chemical growth process is well designed, the simple to apply and reproducible chemical oxidation technique offers a good surface passivation of InP surfaces. In fact, presently, we are not aware of any other window layer material for the InP based cell which offers a better surface passivation and, therefore, a better blue collection efficiency than that obtained using the simple P-rich chemical oxide on a diffused junction homostructure.

In Figure 1 is shown a typical external quantum efficiency plot of a diffused junction p$^+$n(Cd,S)InP cell. The AM0, 25°C V_{oc} of this cell was 887.6 mV, using only a chemically grown P-rich In(PO$_3$)$_3$ oxide

layer as an AR coating. From low frequency EG-V measurements, we recorded a surface state density minimum (N_{ss}) at the Cd-diffused p+-InP/passivating layer interface as low as 2×10^{10} $cm^{-2}eV^{-1}$, which is lower than other previously published values. Such a low N_{ss} value is in excellent qualitative agreement with the high measured V_{oc} and blue response values of these cells. Even after irradiating the cells with 10^{13} cm^{-2}, 3 MeV protons and with energetic α particles with 1.06×10^{17} cm^{-2} equivalent 1 MeV electrons, by using these $In(PO_3)_3$-rich chemical oxides as passivating layer, the drop in the blue response was significantly lower compared to cells without this oxide layer This means that the chemically grown P-rich oxide/InP interface is stable even after exposing the cell to such extreme radiation environments. The cells had also a very good UV stability and a higher radiation tolerance and better annealing properties under working conditions compared to any other InP cell structures.

The main optoelectronic characteristics of this chemically grown P-rich $In(PO_3)_3$ oxide include: (i) high transparency, with an estimated bandgap of 6.8 eV over the visible range of the solar spectrum, (ii) lower than 27% blue reflectivity and average surface reflection of 25% (for an oxide thickness of about 40 nm), and (iii) an average refractive index over 300 to 1000 nm wavelength range of 1.496 with a very small extinction coefficient. These properties, combined with its excellent passivating properties mentioned above, make this chemical oxide very attractive, indeed, for use as the first layer AR coating. Based on experimental ellipsometry and reflectivity data, we demonstrated that the reflectance of the InP cells can be reduced to less than 4% (not including the reflection from the grid metallization) by designing a three-layer AR coating using the P-rich $In(PO_3)_3$ oxide as the first layer, Al_2O_3, ZnS or Si_3N_4 as the second layer and MgF_2 as the third layer. The proposed three-layer AR coatings designs shown in Figure 2 are optimized for minimum current loss of the p^+n InP solar cell under AM0 light spectrum.

GaAs Solar Cells

Our very preliminary data show that using a simple room temperature wet chemical technique, under development at SPECMAT, good quality passivating layers can be grown on GaAs-based surfaces. Although not yet known conclusively, apparently these oxide layers are made up of a top layer which is a mixture of Ga_2O_3 and $GaAsO_4$ and an interfacial layer, which should be rich in a stable $Ga(AsO_3)_3$ oxide, probably mixed with some As_2O_5 component. We have not yet tested these oxides on any GaAs-based solar cells.

Compared to the InP cells, the GaAs-based space solar cells are at a much more advanced stage of development. GaAs based heterostructures also have good lattice matched window layers. Hence, it will be particularly interesting to test the effect of replacing the window layer with chemically grown As-rich layer on BOL and EOL efficiencies of these high efficiency GaAs-based solar cells.

Germanium Cells

Wet chemical oxides grown on Ge surfaces are known to be the worst in terms of their passivating properties and stability. Here, we demonstrate that it is possible to stabilize the chemically grown passivating oxides even in the worst case scenario, namely, Ge cells with front surfaces covered with a chemically formed porous Ge.

Under a 6 month Phase I Clean Car Initiative, awarded to CSU, we fabricated planar n^+pp^+Ge cells. Due to their very good performance parameters (e.g. a record high short circuit current density of 55.5 mA/cm^2, measured at NASA LeRC under AM0, 25^oC conditions on a 1 cm^2 n^+pp^+ Ge cell with no AR coating except for a thin chemically grown passivating layer), these cells appear to have good potential for high efficiency, low cost TPV applications.

In Fig. 3 is shown the EC-V net majority carrier concentration depth profiling of the front n^+p junction of an optimized $n^+pp^+Ge(As,In)$ diffused structure. We used electrochemical characterization techniques for the step-by-step diffusion process optimization. The AM0, $25^\circ C$ short circuit current density of a planar Ge cell using the above structure and a 750 A thick SiO single layer AR coating was only 28.7 mA/cm^2. From the external quantum efficiency of this cell, shown in Fig. 4, it is evident that this device has a poor current collection at the surface, indicating a need for surface passivation.

We first tried growing a very thin (less than 100 A) chemical oxide on a Ge cell with a thin porous layer on the emitter surface. This resulted in severe UV instability. We have been able to essentially eliminate this instability as well as remarkably improve the cell performance by adding a wet chemical step of stabilizing this oxide layer.

After stabilizing the thin chemical oxide using a wet chemical treatment, for a cell made from a Ge structure identical to the one in Figs. 3 and 4, a record high short circuit current density of 55.5 mA/cm^2 was measured at NASA LeRC under AM0, $25^\circ C$ conditions. The external quantum efficiency of this cell is shown in Figure 5 and its spectral response in Figure 6. Note the significantly improved short-wavelength response, indicating excellent collection at the surface. The n^+pp^+ Ge cells had a total area (defined by deep etching - about 5μm into the base, using a mesa etching mask) of 1 cm^2. After the chemical treatment the chemical oxide layer became stable and the UV instability was significantly reduced. The chemical reactions of all three wet chemical processes, namely porous Ge growth, oxide growth, and stabilizing of the oxide are compatible with the Au-based front and back cell contacts.

From our preliminary results, it is obvious that treated chemical oxides grown on Ge front cell surface after the front grid metallization can be used not only for surface passivation, but as an effective first layer AR coating as well.

Concentrator Silicon Solar Cells

The only high efficiency concentrator solar cells available to us for this preliminary experiment were some Vertical MultiJunction (VMJ) Si solar cells, provided by PhotoVolt, Inc. The biggest contributor to efficiency loss in the Si VMJ cell structure is the fact that its illuminated and back surfaces are high recombination surfaces with exposed junctions which are difficult to passivate by means of thermal oxidation. This is because thermal oxidation needs a temperature that is higher than the temperature at which the stack is alloyed together. Additionally, as known for these cells, degradation by nonionizing (subbandgap) radiation (as far as the insulators tantalum pentoxide and silicon nitride are concerned) makes the cell performance parameters decrease significantly with time, especially if UV or near UV radiation are not completely absorbed by the cover glass and/or encapsulant.

On some Si VMJ cells with Ta_2O_5 as an AR coating, after 1 hour exposure to high intensity (about 50 mW/cm^2) near UV light, the drop in the performance parameters was as high as 20%. After the exposure, the cell performance parameters completely recovered after only about 30 minutes, which suggests that fast surface states at the Ta_2O_5/Si interface were responsible for the performance parameters drop. After removing the Ta_2O_5 layer, passivating the surfaces using a chemically grown thin film SiO-based layer, the cell performance parameters increased by as much as 50%. Additionally, no UV degradation was observed even after exposure to the aforementioned halogen light for as long as 5 hours. In fact, for some cells, with similar surface treatments, measurements performed in the PV branch at NASA LeRC under AM0, $25^\circ C$ conditions, showed even a small increase in performance parameters after prolonged light exposure.

CONCLUSIONS

In summary, we show in this paper that using simple, cost-effective room temperature wet chemical techniques to grow passivating layers on the front surface of Ge, Si and InP and GaAs based solar and TPV cells, it is possible to reduce reflection and very significantly improve current collection near the illuminated surface. Based on our results we suggest that replacing the presently used passivating/window layers of high efficiency homo- and heterojunction III-V based space solar cells with stable ultrawide bandgap chemically grown oxide layers will increase both the BOL and EOL efficiencies while decreasing the fabrication cost and increasing the yield of space solar cells. We are confident that through a relatively short R&D effort, stable chemically grown oxides with good passivating and optical properties can be cost effectively and reproducibly grown prior to or after the front metallization step for any other space and terrestrial solar cell and TPV cell configurations.

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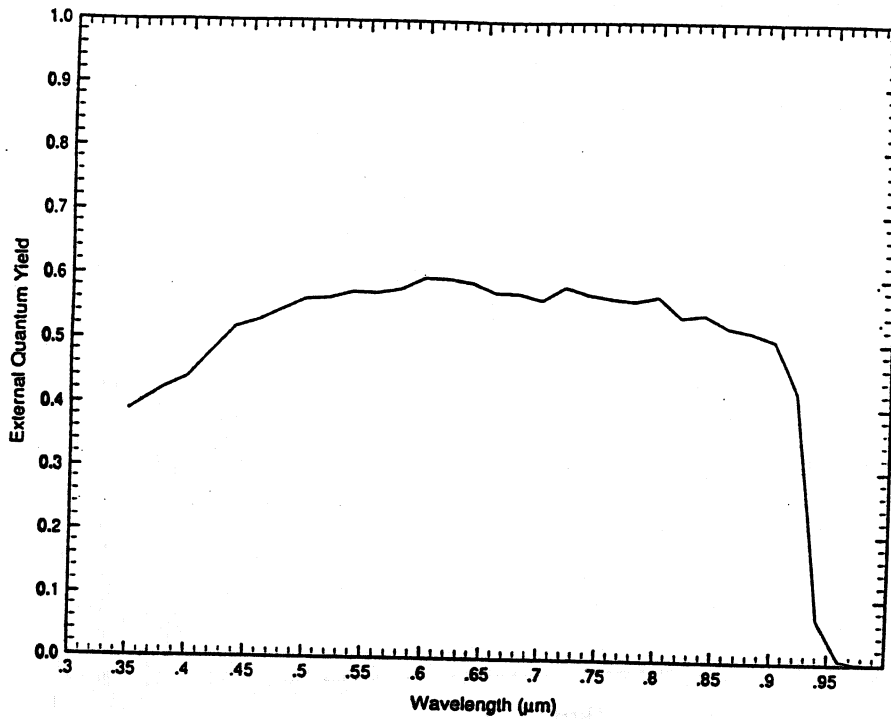
Fig. 1. Typical EQY plot of a diffused junction $p^+n(Cd,S)InP$ cell with a thin (~ 30 nm) chemically grown $In(PO_3)_3$-rich oxide as an AR coating. Overall reflectivity: ~ 30%. Emitter thickness: ~ 0.45μ
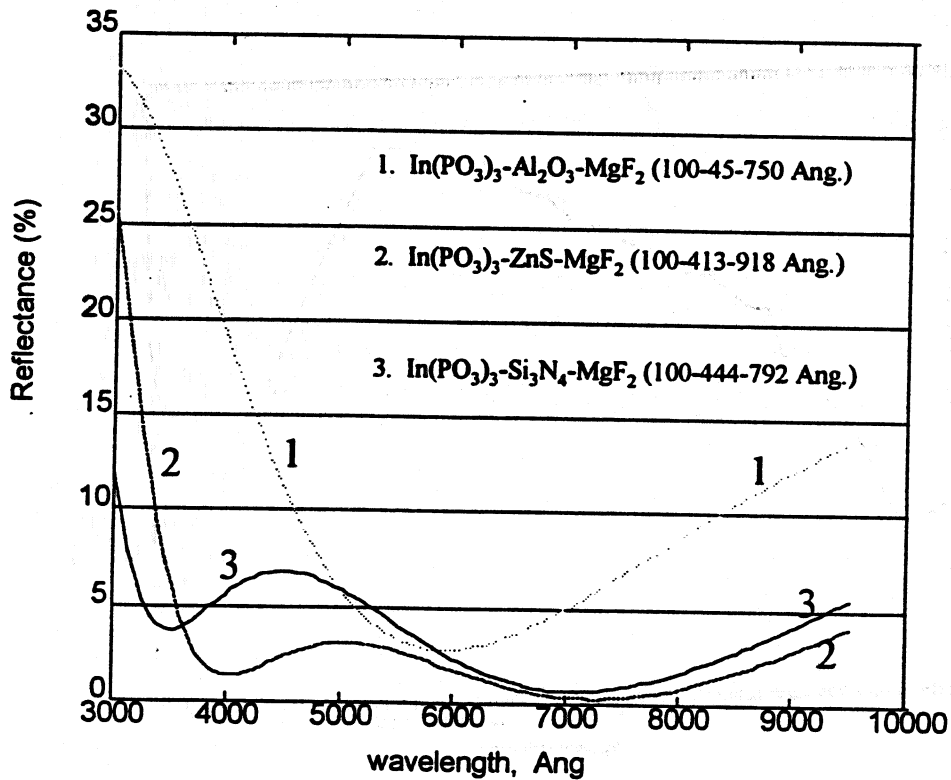

Fig. 2. Surface reflectance of p^+n InP solar cell with optimized 3-layer AR coatings using the passivating $In(PO_3)_3$-rich chemically grown oxide as the first layer.
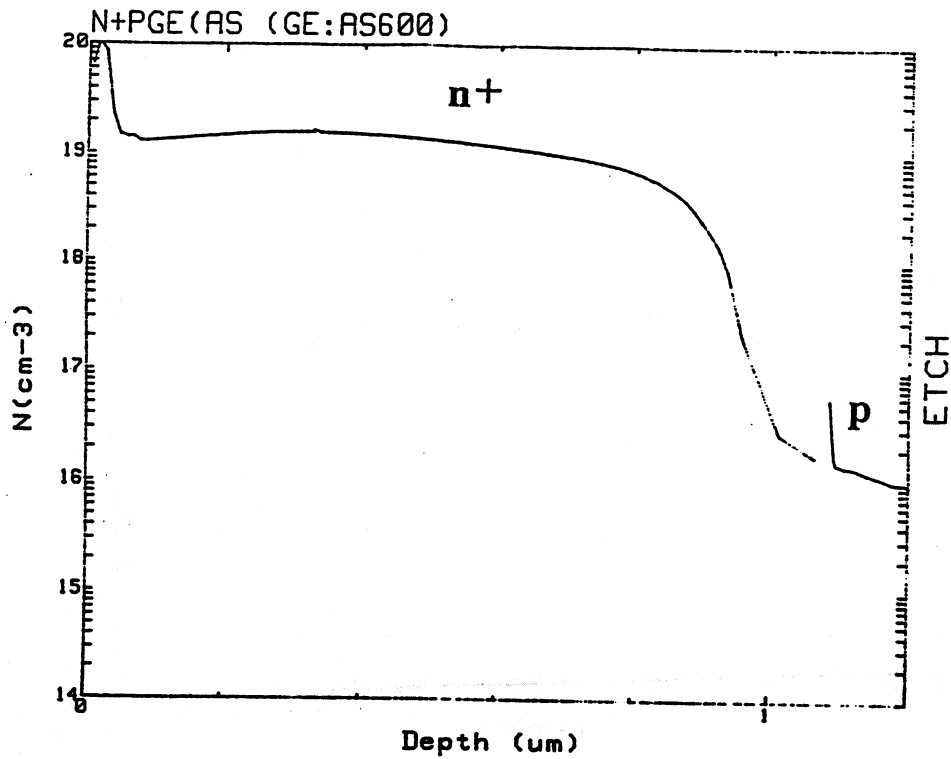
Fig. 3. EC-V net majority carrier concentration depth profile at the front of a n^+pp^+ Ge diffused structure.
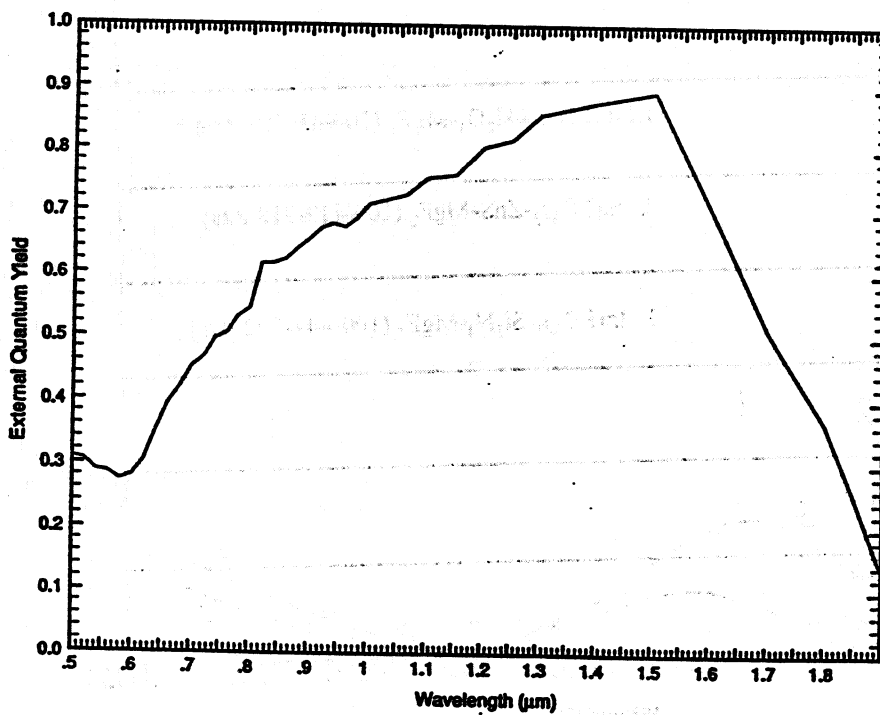

Fig. 4. External quantum efficiency of a planar n^+pp^+ Ge cell fabricated on a structure identical to the one in Fig. 3.
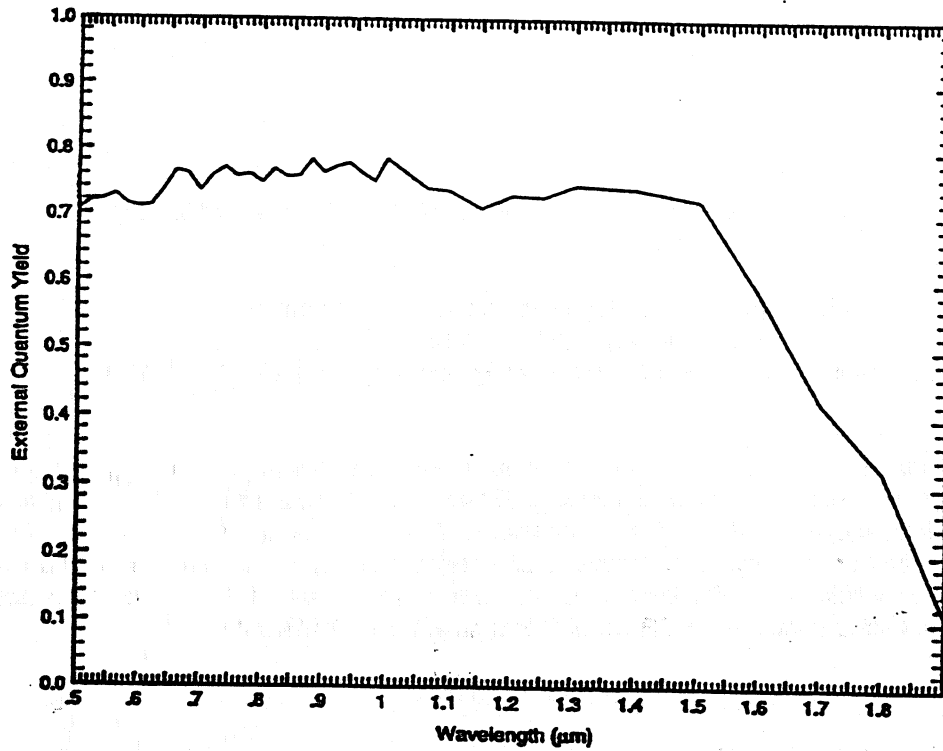
Fig. 5. External quantum efficiency of a planar n^+pp^+ Ge cell fabricated on a structure such as in Fig. 3. after passivating and stabilizing the porous layer.
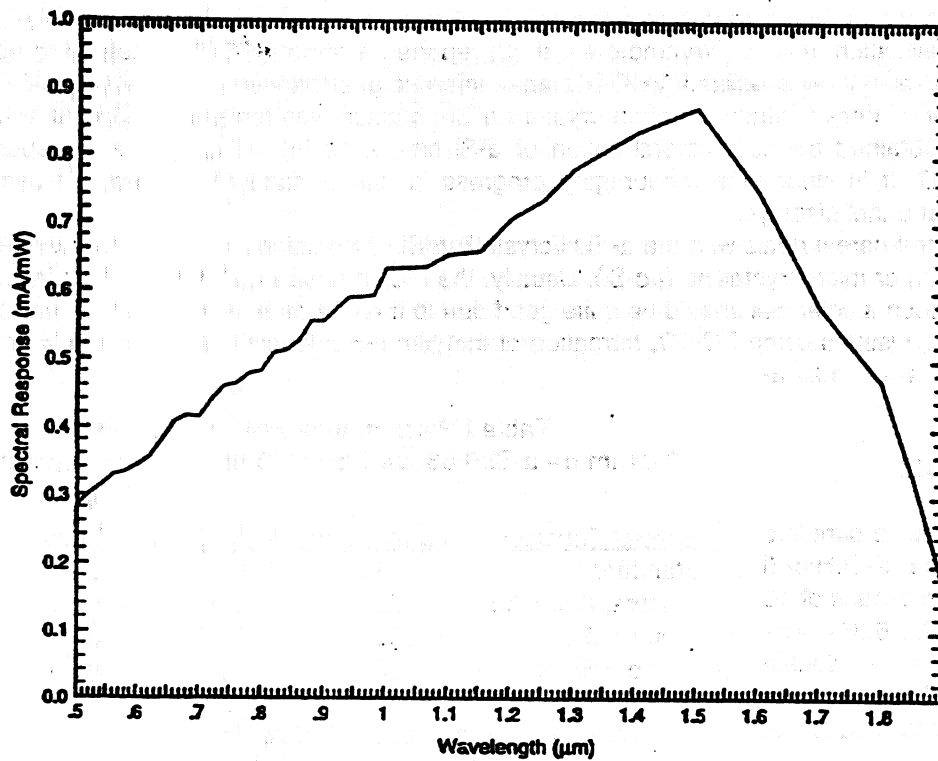

Fig.6. Spectral response of the n^+pp^+ Ge cell in Fig. 5.