Table I. $E_c - E_F$ and $V_{oc}$ for ITO/n-Si solar cells as a function of Si doping concentration.

<table>
<thead>
<tr>
<th>$p$ (n-Si) (Ω cm)</th>
<th>$E_c - E_F$ (eV)</th>
<th>$V_{oc}$ (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>0.24</td>
<td>380</td>
</tr>
<tr>
<td>0.13</td>
<td>0.14</td>
<td>340</td>
</tr>
</tbody>
</table>

layer on the open-circuit photovoltage is two-fold. While the increased value of $I_0$ acts to reduce $V_{oc}$, a concomitant increase in the value of $n$ can result in a net enhanced open-circuit photovoltage. This explanation of the reason for an enhanced $V_{oc}$ with increasing SiO$_2$ thickness is in conflict with that given by Anderson,¹⁰ who ascribes it to a decrease in $I_0$. Since the observed $V_{oc}$ of the device of Fig. 1 is 380 mV, Eq. (1) indicates an $n$ of 4.3. But $n$ can also be obtained from the dark forward $I$–$V$ characteristic via the expression

$$n = \frac{q}{kT} \frac{3V}{\delta \ln I}.$$  (2)

Figure 3 shows the dark forward $I$–$V$ characteristic of the same device as in Figs. 1 and 2. Eq. (2) then yields $n = 3.9$, in good agreement with the value obtained from the photovoltaic measurement. This provides some confidence that the model presented in this paper is essentially correct.

The trend between the values of $E_c - E_F$ in the Si$^{10}$ and the measured $V_{oc}$ as predicted by our band model was tested by fabricating cells on two differently doped n-Si wafers during the same run. The results are shown in Table I. As can be seen, a decrease in $E_c - E_F$ of 100 meV was reflected by a decrease in $V_{oc}$ of 40 mV.

In conclusion, we have fabricated solar cells consisting of rf-sputtered ITO deposited on single-crystalline Si and have measured the $I$–$V$ characteristics in the dark and in the presence of terrestrial sunlight. We have presented a model which quantitatively explains the experimental data.

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Room-temperature operation of GaAs Bragg-mirror lasers

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Room-temperature operation of GaAs distributed Bragg reflector lasers is reported. The diodes are fabricated from conventional double heterostructures involving only a single step of liquid-phase epitaxy. For gratings with a period of 3700 Å, the diodes lased at 8770 Å, which corresponds to the high-absorption side of the spontaneous emission spectrum. Thresholds as low as 6 kA/cm$^2$ have been realized.

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Room-temperature operation of distributed feedback (DFB) lasers has been achieved through the use of separate confinement structures which reduce nonradiative recombination centers. The fabrication of these lasers involves, however, either a growth process of liquid-phase epitaxy (LPE) in two steps¹ or a hybrid combination of liquid-phase epitaxy and molecular-beam epitaxy.² An alternative for separating the corrugations from the active region is to fabricate the gratings on the two sides of the pumped (active) region where they serve as Bragg reflectors. By inserting special modules in the conventional boats used for LPE, Reinhart et al.³ were able to grow tapers that couple light from the active region to a distributed Bragg reflector (DBR) placed on one side. Recently, optically pumped DBR lasers⁴ and injection DBR lasers operating at 185 K⁵ have been reported. In this letter, we report room-temperature operation of double-heterostructure (DHS) DBR lasers that are fabricated from wafer structures grown in a step of LPE using conventional techniques.

The laser structure is shown in Fig. 1(a). The laser diodes were grown with a starting temperature of 805°C and a cooling rate of 0.1–0.4°C/min. The first solution was cooled 6–8°C before contact with the Si-doped n-GaAs substrate. By varying the length of time that the substrate is in contact with the second solution (less than 1 min) and by using a slow cooling rate, the thickness of the active region can be controlled with preci-
we find that the diodes with part of their gratings pumped have slightly lower thresholds than those with passive Bragg mirrors.

Diodes with cleaved as well as with saw-cut end faces were studied. One of the diodes, with a grating period \(\Lambda\) of 3721 Å lased at 8953 Å, 100 Å away from the peak of the spontaneous emission spectrum. The emission spectrum of the diode is shown in Fig. 2 for different pumping currents. Using the Bragg condition of \(n_{e,i} \Lambda = n_{g} \Lambda\), where \(n_{e,i}\) is the effective waveguide index and \(\lambda\) is the lasing vacuum wavelength, we obtain an effective guide index of 3.6. The emission spectrum for 18.4 A corresponds to \(I = 1.2T_{m}\). Two dominant modes, approximately 3 Å apart, can be resolved. Fabry-Perot lasers fabricated from the same crystal show lasing at or much nearer the spontaneous emission peak.

Other diodes, with a smaller period of 3700 Å, lased at shorter wavelengths. The emission spectrum of two diodes with gratings fabricated by the same holographic exposure are shown in Figs. 3(a) and 3(b). The pumping current is approximately 1.2 times the threshold current. The gratings' lengths are \(\sim 150 \mu\) at the output side and \(\sim 700 \mu\) at the other side. The lasing wavelength was at 8770 Å which corresponds to the high-energy side of the spontaneous emission peak (8970 Å). This provides good evidence for optical feedback by the gratings in these lasers since the short-wavelength side of the spontaneous emission peak corresponds to the high-absorption side of the spectrum. Lasers with feedback provided by cleavage planes, thus having no Bragg frequency selectivity, have their lowest-threshold mode at the long-wavelength low-absorption side. The corresponding effective guide index for these DBR lasers is 3.55.

There are most likely unresolved modes within the lasing bandwidth near 8770 Å for the diodes shown in Figs. 3(a) and 3(b). The bandwidth (\(\Delta \lambda_{DBR}\)) of the central reflection peak of the grating mirror increases with both the coupling constant \((k)\) and its loss \((\alpha)\). As a rough estimate, \((\Delta \lambda_{DBR})\) is given approximately by \((\Delta \lambda_{DBR}) = (\lambda^2/n_{at}^2)/(k^2 + \alpha^2)^{1/2}\), where \(n_{at} = n[1 - (\lambda/n) \times (dn/d\lambda)]\) is the index of refraction with dispersion.
than further away [Fig. 1(b)]. This results in a gentle tapering of the \( \rho \)-GaAlAs superstrate layer towards the edge of the mesa. The tapering presents experimental difficulty in reducing the separation between the corrugation and the active waveguiding layer, since an active layer that is etched near the mesa is rough and leads to poor waveguiding. We expect that with the use of preferential etch, such as superoxol\(^7\) for GaAs and "gold etch" for GaAlAs,\(^8\) the separation between the corrugations and the active layer can be controlled precisely. With such control, increasing the coupling constant for distributed feedback and thus reducing the threshold current should be feasible.

In conclusion, we have demonstrated room-temperature operation of DBR lasers where optical feedback is provided by a pair of Bragg mirrors. Fabrication of such diodes involves only a single step of LPE using conventional techniques, and the lasers retain the frequency selectivity of their Bragg reflectors.

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\(^12\)Wong-Tien Tsang and Shyh Wang, Appl. Phys. Lett. 28, 596 (1976).


\(^15\)J. Dyment (private communication).