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

ρ (n-Si) (Ω cm)	$E_c - E_F$ (eV)	V_{oc} (mV)
5.1	0.24	380
0.13	0.14	340

layer on the open-circuit photovoltage is two-fold. While the increased value of I_s 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_x thickness is in conflict with that given by Anderson,[1,8] who ascribes it to a decrease in I_s.

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

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

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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†German Academic Exchange Fellow.

[1]R.L. Anderson and R.W. Ahrons, Report NSF/RANN/SE/AER 74-17631/PR/74/4/-75/2/ (unpublished).
[2]J.B. Dubow, D.E. Burk, and J.R. Sites, IEDM 1975 Technical Digest, p. 230 (unpublished).
[3]D.B. Fraser and H.D. Cook, J. Electrochem. Soc. **119**, 1368 (1972).
[4]J.C.C. Fan and F.J. Bachner, J. Electrochem. Soc. **122**, 1719 (1975).
[5]T. Mizrah, Sc.D. thesis (MIT, 1976) (unpublished).
[6]V.M. Vainshtein and V.I. Fistul, Sov. Phys.-Semicond. 1 104 (1967).
[7]S.M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1969).
[8]R.L. Anderson, Appl. Phys. Lett. 27, 691 (1975).
[9]H.C. Card and E.H. Rhoderick, J. Phys. D 4, 1589 (1971).
[10]H.I. Wolf, *Silicon Semiconductor Data* (Pergamon, New York, 1969).

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 steps[1] 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 lasers[4] and injection DBR lasers operating at 183 °K [5] 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-

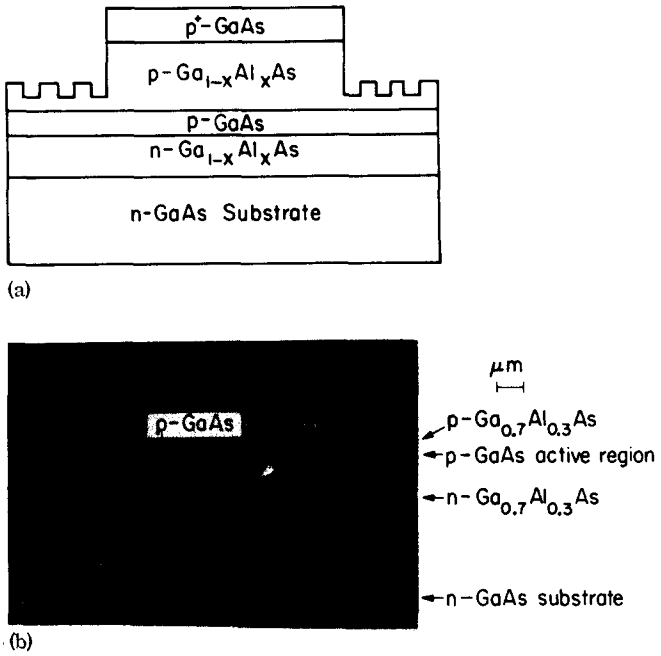


FIG. 1. (a) Schematic drawing of a distributed Bragg reflector laser. (b) Cross section of the mesa by SEM.

sion. Active region thicknesses near 600 Å with Fabry-Perot laser thresholds as low as 900 A/cm^2 at room temperature have been obtained. Typical thicknesses for the diodes used in our DBR laser experiments are n-$Ga_{0.7}Al_{0.3}As$ ~ 2 μ; p-GaAs (active layer) ~(0.2–0.4) μ; p-$Ga_{0.7}Al_{0.3}As$ ~(1–1.5 μ); and p^+-GaAs ~1 μ.

A mesa [Fig. 1(b)] was then etched out starting from the surface layer down to the p-GaAlAs layer by a solution of H_2SO_4:H_2O_2:H_2O (4:1:1). Shipley AZ1350 photoresist diluted by a thinner in a ratio of 1:2 was then spun on the wafer. A photoresist grating mask (Λ ~ 3700 Å) was then laid on both sides of the mesa by holographic exposure using the 4416-Å line of the He-Cd laser. The corrugations for optical feedback were then etched out by a Br_2:CH_3OH (less than 0.1%) etch.[6] Silicon dioxide (less than 0.5 μ) was sputtered and a window opened at the center for metallic contact to the active part of the diode. The samples were then lapped down to 100 μ. For contact, Au:Ge (88% Au, 12% Ge) was evaporated on the n side and a Ag:Mn alloy (96% Ag, 4% Mn) on the p side. The individual lasers were mounted in indium-plated copper heat sinks. Our typical diode has a mesa of width ~500 μ, gratings of length 100–300 μ at the output side, and 500–700 μ at the other side of the mesa. The lasers were tested at room temperature with driving pulses of width ~110 nsec and a repetition rate of 150/sec.

We have experimented with diodes in which the grating regions were not current pumped, as well as with diodes with larger central contact windows, thus having current flow through the grating. We find that the lasers with completely passive gratings have threshold current densities of 6–7 kA/cm^2, which is 2–3 times higher than that of our Fabry-Perot lasers fabricated from the same wafer. Based on calculations using the area of the central contact window as the pumped area, 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 (Λ) 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 $n_{eff} = 3\lambda/2\Lambda$, where n_{eff} is the effective waveguide index and λ is the lasing vacuum wavelength, we obtain an effective guide index of 3.6. The emission spectrum for 18.4 A corresponds to $I = 1.2 I_{th}$. 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 ~150 μ at the output side and ~700 μ at the other side. The lasing wavelength was at 8770 Å which corresponds to the high-energy side of the spontaneous emission peak (8790 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 (α). As a rough estimate, $(\Delta\lambda)_{DBR}$ is given approximately by $(\Delta\lambda)_{DBR} = (\lambda^2/n_{dis}\pi)(K^2+\alpha^2)^{1/2}$, where n_{dis} $(= n[1-(\lambda/n) \times (dn/d\lambda)])$ is the index of refraction with dispersion

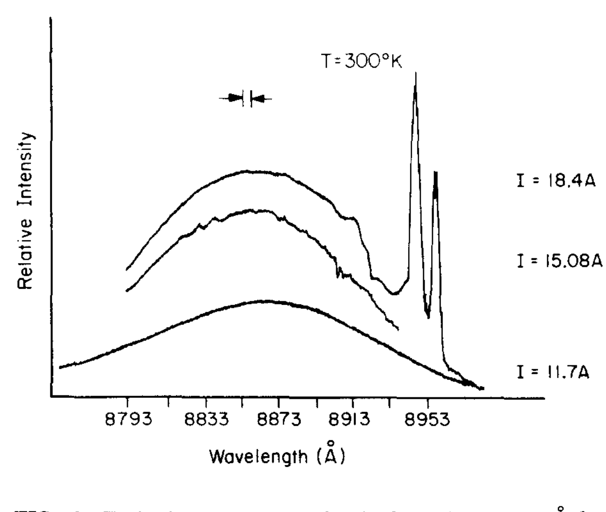
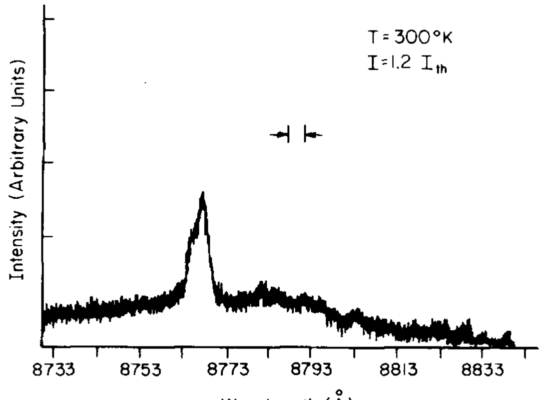
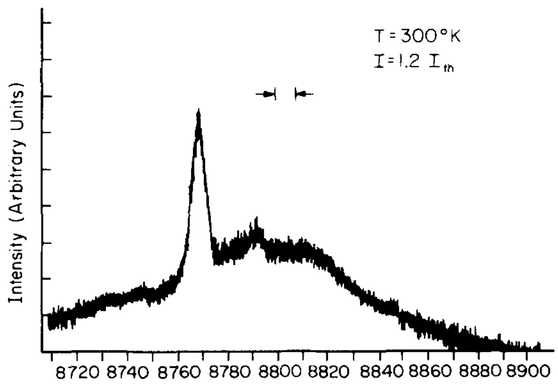


FIG. 2. Emission spectrum of a diode with Λ = 3721 Å for different pumping currents up to $I \sim 1.2 I_{th}$.



(a)



(b)

FIG. 3. (a) and (b) Emission spectrum of two diodes with $\Lambda = 3700$ Å at $I = 1.2 I_{th}$.

taken into account. The typical full bandwidth of our DBR lasers is 7–8 Å. Using values of K based on estimates from scanning electron microscope observations of the grating profile, we find as expected, that the elimination of taper coupling[3] introduces rather lossy reflectors at their own lasing wavelength. Calculation of the threshold gain relative to that of Fabry-Perot lasers, based on such estimates of α and K, agrees well with our experimental results.

We have also found experimentally that the p-GaAlAs layer tends to be etched slightly deeper near the mesa than further away [Fig. 1(b)]. This results in a gentle tapering of the p-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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[1]K. Aiki, M. Nakamura, J. Umeda, A. Yariv, A. Katzir, and H.W. Yen, Appl. Phys. Lett. 27, 145 (1975).

[2]H.C. Casey, Jr., S. Somekh, and M. Illegems, Appl. Phys. Lett. 27, 142 (1975).

[3]F.K. Reinhart, R.A. Logan, and C.V. Shank, Appl. Phys. Lett. 27, 45 (1975).

[4]H.W. Yen, W. Ng, I. Samid, and A. Yariv, Opt. Commun. 7, (No. 3), 213 (1976).

[5]Won-Tien Tsang and Shyh Wang, Appl. Phys. Lett. 28, 596 (1976).

[6]M. Nakamura, K. Aiki, J. Umeda, A. Katzir, A. Yariv, and H.W. Yen, IEEE J. Quantum Electron. **QE-11**, 436–439 (1975).

[7]R.A. Logan and F.K. Reinhart, J. Appl. Phys. 44, 4172 (1973).

[8]J. Dyment (private communication).