practical importance. cw operation above 77 K has become possible. With He closed-cycle coolers quite a large temperature tuning range has become available to these lasers.

The authors wish to thank D. Daniel, H. Henkel, R. Herkert, Mrs. B. Junkersfeld, W. Kopmeier, H. Pfeiffer, and H.-D. Wurzinger for their valuable technical assistance. This work was financially supported by the Ministry of Research and Technology of the Federal Republic of Germany as part of its technology program (NT 635).

[1]E.D. Hinkley, Opto-Electron. **4**, 69 (1972).
[2]H. Preier and W. Riedel, Appl. Phys. Lett. **25**, 55 (1974).
[3]J.F. Butler and A.R. Calawa, in *Physics of Quantum Electronics*, edited by P.L. Kelley, B. Lax, and P.E. Tannenwald (McGraw-Hill, New York, 1966) p. 458.
[4]J.M. Besson, J.F. Butler, A.R. Calawa, and R.H. Rediker, Appl. Phys. Lett. **7**, 206 (1965).
[5]J. Hesse and H. Preier, in *Festkörperprobleme XV*, edited by H.J. Queisser (Vieweg, Braunschweig, Germany, 1975), p. 229.
[6]K.J. Sleger, G.F. McLane, and D.L. Mitchell, J. Nonmetals **1**, 297 (1973).
[7]J.N. Walpole, A.R. Calawa, R.W. Ralston, T.C. Harman and J.P. McVittie, Appl. Phys. Lett. **23**, 620 (1973).
[8]L.R. Tomasetta and C.G. Fonstad, Appl. Phys. Lett. **25**, 440 (1974).
[9]S.H. Groves, K.W. Nill, and A.J. Strauss, Appl. Phys. Lett. **25**, 331 (1974).
[10]G.F. McLane and K.H. Sleger, J. Electron. Mater. **4**, 465 (1975).
[11]K. Duh and H. Preier, Thin Solid Films **27**, 247 (1975).
[12]K. Duh and H. Preier, J. Mater. Sci. **10**, 1360 (1975).
[13]H. Preier, R. Herkert, and H. Pfeiffer, J. Cryst. Growth **22**, 153 (1974).
[14]G. Lasher and F. Stern, Phys. Rev. A **133**, 553 (1964).
[15]L.R. Tomasetta and C.G. Fonstad, IEEE J. Quantum Electron. **QE-11**, 384 (1975).
[16]I. Hayashi, Appl. Phys. **5**, 25 (1974).
[17]Yu.I. Ravich, J. Phys. Suppl. C4, **29**, 114 (1958).
[18]W.B. Joyce and R.W. Dixon, J. Appl. Phys. **46**, 855 (1975).
[19]H. Preier and W. Riedel, J. Appl. Phys. **45**, 3955 (1974).

Amorphous silicon solar cell

D. E. Carlson and C. R. Wronski

RCA Laboratories, Princeton, New Jersey 08540
(Received 6 February 1976)

Thin film solar cells, ~1 μm thick, have been fabricated from amorphous silicon deposited from a glow discharge in silane. The cells were made in a *p-i-n* structure by using doping gases in the discharge. The best power conversion efficiency to date is 2.4% in AM-1 sunlight. The maximum efficiency of thin-film amorphous silicon solar cells is estimated to be ~14–15%.

PACS numbers: 84.60.Jt, 68.50.+j

Efficient thin-film solar cells offer a distinct cost advantage over those formed from single crystals and could become competitive with conventional sources of power. In this paper, we report on the development of a new type of thin-film solar cell, ~1 μm thick, that utilizes amorphous silicon (*a*-Si) deposited from a glow discharge in silane (SiH_4). We have achieved a power conversion efficiency of 2.4% in AM-1 sunlight by using an *a*-Si *p-i-n* structure.

An efficient thin-film solar cell requires (i) absorption of a large fraction of the incident solar radiation, (ii) the efficient collection of both photogenerated electrons and holes, (iii) a junction with a built-in potential on the order of 1 V, and (iv) a low internal series resistance. We chose to examine discharge-produced *a*-Si as a potential solar cell material because of its unusual electrical and optical properties.

Discharge-produced *a*-Si was first studied by Chittick *et al.*[1] who observed a much larger photoconductive effect than observed in evaporated or sputtered *a*-Si. Subsequently, LeComber and Spear[2,3] showed that the electron drift mobility was on the order of 0.1 cm^2/Vs and that the density of states within the gap decreased with increasing deposition temperature. When deposited at temperatures $\gtrsim 200\,^\circ C$, discharge-produced *a*-Si was shown to possess a much smaller density of bonding defects than other amorphous semiconductors. The absorption coefficient has been measured for $\lambda > 0.55$ μm,[4] and the data show that most of the radiation with $\lambda < 0.7$ μm is absorbed in a film on the order of 1 μm thick. Moreover, the optical band gap of *a*-Si is 1.55 eV which is close to the optimum value for photovoltaic energy conversion in semiconductor homojunctions.[5]

Luminescence measurements at 77 °K by Engemann and Fischer[6] showed that the radiative quantum efficiency approached unity for films deposited above 200 °C, while no luminescence was observed in evaporated *a*-Si films. Recently, Spear *et al.*[7,8] have reported that the electrical properties of discharge-produced *a*-Si can be controlled by substitutional doping and that *p-n* junctions can be formed in *a*-Si. Similar junctions have been fabricated in our laboratories with the emphasis placed on solar cell applications.

Our devices were fabricated by depositing discharge-produced *a*-Si on substrates of indium-tin-oxide (ITO) coated glass at deposition temperatures of 250–400 °C. The surface resistivity of the ITO coatings was ~2–5 Ω/□, so current collection grids were not necessary

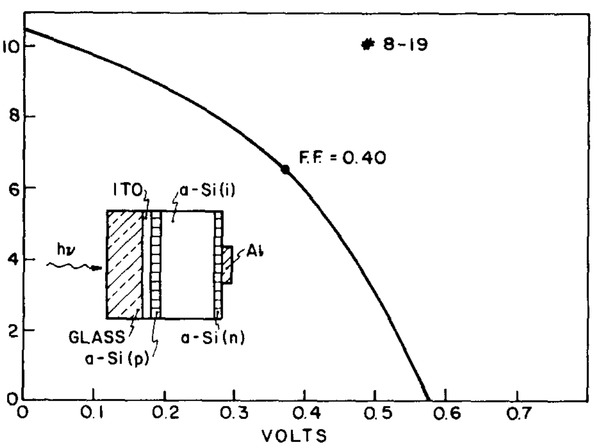

FIG. 1. Current-voltage curve for device #8-19 under illumination comparable to AM-1 sunlight. Also included in the figure is a schematic diagram of a p-i-n structure.

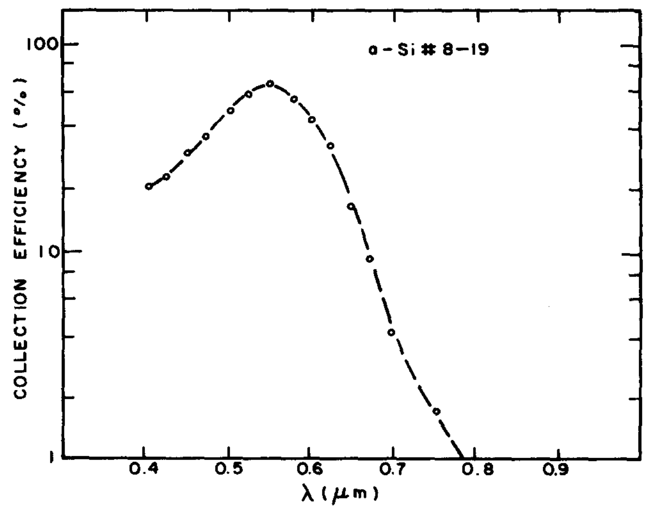

FIG. 2. Collection efficiency as a function of wavelength for device #8-19.

for the device areas employed. A typical solar cell structure involved first depositing a few hundred angstroms of boron-doped a-Si from an atmosphere containing SiH_4 and ~1% B_2H_6. Then an "intrinsic" or undoped layer on the order of 1 μm in thickness was deposited, and then several hundred angstroms of phosphorus-doped a-Si was deposited from SiH_4 containing ~1% PH_3. Finally, an Al electrode was evaporated onto the p-i-n structure to form a low-resistance contact to the n layer. A schematic of the structure is shown in Fig. 1.

Also shown in Fig. 1 is a current-voltage curve of device (#8-19) measured in light from a tungsten-filament lamp. The composite a-Si film was ~1.6 μm thick and the electrode area was 5×10^{-3} cm^2. The lamp was adjusted to give the same value of the short-circuit current density (j_{sc}) as AM-1 sunlight (the open-circuit voltage V_{oc} and the fill factor F.F. were the same as in sunlight). The power conversion efficiency was estimated to be 2.4 (±0.2)% in AM-1 sunlight (~100 mW/cm^2) as measured with a calibrated single-crystal silicon solar cell. A similar large-area cell (~3.5 cm^2) had a conversion efficiency of ~1.1% in AM-1 sunlight.

Figure 2 shows the collection efficiency of device #8-19 measured with a Bausch and Lomb monochromator calibrated with a thermopile. The short-circuit photocurrent was linear over the investigated range of intensities, 10^{-4} to 1 sun. The decrease in collection efficiency at short wavelengths is apparently due to recombination in the p layer. The decrease at the longer wavelengths is due to the lower absorption coefficient as shown by the data in Fig. 3. Good agreement is obtained in the overlap region with the absorption data of Loveland *et al.*[4] Figure 3 also shows that the absorption coefficient of a-Si exceeds that of crystalline Si over the wavelength range of 0.315–0.75 μm and is an order of magnitude higher over a significant portion of that region. These data can be used to calculate the maximum value of j_{sc} that can be obtained under AM-1 illumination. For a single pass of radiation through 3 μm of a-Si, the maximum value of j_{sc} is ~22 mA/cm^2. The same value is obtained for a device 1.5 μm thick when the unabsorbed radiation is reflected at the back contact.

The largest value of j_{sc} (AM-1) measured at room temperature was 10.5 MA/cm^2 (see Fig. 1), but the same device at 125°C exhibited a value of 14 mA/cm^2. This increase in j_{sc} with heating was observed in most devices and indicates that some photogenerated carriers are being trapped giving rise to an effective series resistance. This series resistance has limited our fill

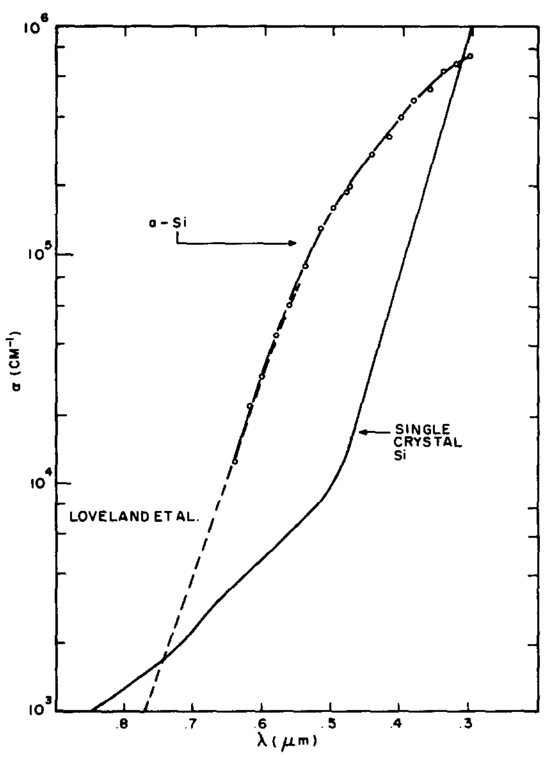

FIG. 3. The optical absorption coefficient as a function of wavelength for discharge-deposited a-Si and single-crystal Si. Dashed curve represents data of Loveland *et al.* Solid line is present work.

factors to $\lesssim 0.45$. The short-circuit current did not improve for a-Si films thicker than ~1 μm, indicating that the diffusion length of holes is $\lesssim 1$ μm. Moreover, j_{sc} was reduced if the "intrinsic" layer were doped with either boron or phosphorus, indicating a reduction in diffusion length with doping.

For forward biases in excess of ~0.5 V, the dark current density obeyed the expression $J \propto V^n$, where n was ~3. This result can be explained by space-charge-limited conduction due to a trap distribution that decreases exponentially toward midgap.[9] For forward bias $\lesssim 0.5$ V, a fit of the expression

$$j = j_0[\exp(eV/\beta kT) - 1] \quad (1)$$

to the dark I-V characteristics yielded values of $\beta \gtrsim 2$, indicating that the current transport in these devices is recombination limited.

The largest observed value of the open-circuit photovoltage V_{oc} was 790 mV in light comparable to AM-1 sunlight. This value may be close to the practical limit since it may be difficult to utilize the entire energy (or mobility) gap due to the tail states. That is, although the optical gap is estimated to be ~1.55 eV, the density of tail states increases rapidly within ~0.2 eV of the extended states.[3] Thus, it is difficult to move the Fermi level closer than ~0.2 eV to E_c or E_v, as confirmed by the luminescence[6] and electrical conductivity data.[7] V_{oc} was found to obey the logarithmic relation $V_{oc} = (\beta' kT/e)\ln F$ where F is the relative light intensity and $\beta' \sim 1.5$.

The theoretical limit for the efficiency of thin-film a-Si solar cells can be estimated by assuming that the limits for V_{oc} and j_{sc} are 800 mV and 22 mA/cm^2, respectively. Since the theoretical limits for the fill factor are 0.78–0.87 (for $\beta' = 2$ to 1),[10] the maximum efficiency is estimated to be ~14–15%.

In summary, a-Si solar cells have been fabricated in p-i-n structures with conversion efficiencies as high as 2.4%. Further development of these devices could lead to a low-cost solar cell for terrestrial applications.

The authors gratefully acknowledge the contributions of P.J. Zanzucchi for the opttical absorption measurements; A.R. Triano and R.E. Daniel for their technical assistance; D. Hoffman, B. Halon, and F. Tams for performing the vacuum evaporations; and A.R. Moore for helpful discussions.

[1]R.C. Chittick, J.H. Alexander, and H.F. Sterling, J. Electrochem. Soc. **116**, 77 (1969).
[2]P.G. LeComber and W.E. Spear, Phys. Rev. Lett. **25**, 509 (1970).
[3]W.E. Spear and P.G. LeComber, J. Non-Cryst. Solids **8-10**, 727 (1972).
[4]R.J. Loveland, W.E. Spear, and A. Al-Sharboty, J. Non-Cryst. Solids **13**, 55 (1973/74).
[5]Joseph J. Loferski, J. Appl. Phys. **27**, 777 (1956).
[6]D. Engemann and R. Fischer, in *Proceedings of the 12th International Conference on the Physics of Semiconductors* (Teubner, Stuttgart, 1974).
[7]W.E. Spear and P.G. LeComber, Solid State Commun. **17**, 1193 (1975).
[8]W.E. Spear, P.G. LeComber, S. Kinmond, and M.H. Brodsky, Appl. Phys. Lett. **28**, 105 (1976).
[9]A. Rose, *Concepts in Photoconductivity and Applied Problems* (Interscience, New York, 1963).
[10]J. Lindmeyer, COMSAT Tech. Rev. **2**, 105 (1972).

Capacitance and *R-C* time constant of a nearly pinched-off semiconducting channel in the high-frequency regime*

Kurt Lehovec and Nasser Zamani

University of Southern California, Los Angeles, California 90007
(Received 5 February 1976)

The gate capacitance of a nearly pinched-off semiconducting channel located between gate and substrate depletion layers is derived for the high-frequency regime in which the substrate charge does not change with ac channel charge. The distance corresponding to the inverse gate capacitance exceeds the gate depletion layer width, and the R-C time constant per unit channel length approaches the inverse of the product of channel carrier mobility and voltage equivalent of temperature. Ordinary C-V analysis at high frequency provides an artifactitious impurity profile which is fairly independent of the doping concentration and of the substrate and which varies in proportion to absolute temperature. Reconstruction of the true impurity profile from this artifactitious profile is discussed.

PACS numbers: 73.40.Lq, 73.30.+y, 85.30.Tv, 72.30.+q

Depletion mode field effect transistors comprise a semiconducting channel bounded on one side by a gate depletion layer and on the other side by an insulating substrate (sapphire for silicon-on-sapphire devices, and Cr-doped GaAs for GaAs devices). The substrate interface is usually lined by a depletion layer, which either arises from surface states or is due to a contact potential difference. The base layer of a planar bipolar