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AMORPHOUS SILICON DEVICES FOR CONSUMER APPLICATIONS

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1 INTRODUCTION

The technology of semicodncutor devices, particularly of integrated circuits (IC), which has been responsible for the development of modern electronics, is based on the technique of growing single crystalline silicon. Progress in IC technology has been measured by the fineness and exactness with which a functional transistor unit is formed on the silicon substrate. However, the growth and purification of single crystals requires many processing steps as well as a considerable amount of heat energy, and there is a certain limit to the size of the crystals obtained. Amorphous semiconductor technology provides an effective substitute for the shortcomings of single crystalline silicon technology.

Since the configuration of atoms in an amorphous material has no periodicity as is found in crystals, amorphous semiconductor layers can be formed on a large area substrate in a relatively simple manner. A traditional amorphous product is the photoreceptor used in electronic copying machines, based on vacuum-evaporated amorphous selenium film. Today, amorphous silicon (a-Si) with its wide range of potential applications is the most prominent amorphous semiconductor. The application of a-Si that first drew attention was the thin-film solar cells; photoreceptors for electrophotography followed. Fuji Electric has been developing a low-cost solar cell for photovoltaic power generation as part of the government sponsored "Sunshine Project." It was also successful in developing a photoreceptor for electrophotography. These will be discussed elsewhere.

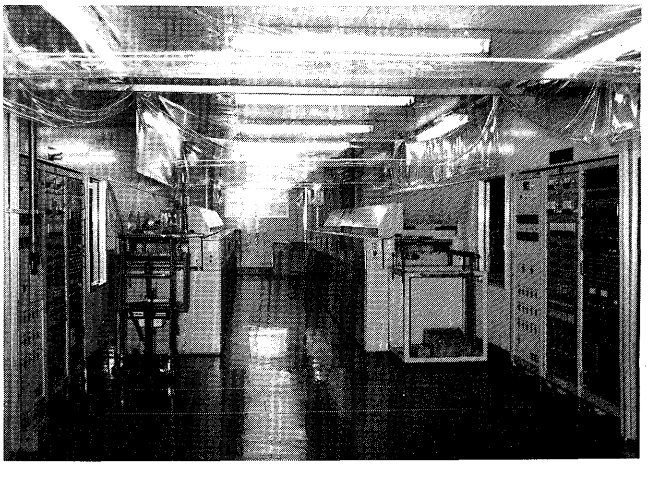
Amorphous-Si devices for consumer applications were first commercialized by Fuji Electric.[1] They include solar cells for hand-held calculators, watches, battery chargers, as well as photosensors. A description of these products is presented in the following chapters.

2 PREPARATION AND CHARACTERISTICS OF a-Si FILMS

The silicon atoms in a-Si networks are not regularly spaced. Therefore the Si-Si bonds are not regular as they would be in a crystal, and there exist a number of dangling bonds. Obviously the abundance of dangling bonds, which are in fact defects, renders the material useless as a semiconductor. However, the presence of hydrogen, used in the growth process, nullifies the defects through the formation of silicon-hydrogen bonds. Thus, defect-free a-Si with acceptable electrical characteristics contains 10 to 20% hydrogen. A variety of techniques for the production of hydrogenated a-Si has been proposed. Fuji Electric employes the plasma CVD, or glow discharge method in the production of consumer products, in which gaseous silance (SiH_4) is decomposed by the glow discharge method, induced by a radio frequency (13.5 MHz) electrical field. The a-Si layer is deposited on a substrate heated to 200 to 300°C. Silane, doped with diborane (B_2H_6) or phosphine (PH_3), results in p-type or n-type film respectively. Thus switching gases will automatically yield a p-i-n structure, which is fundamental in a solar cell. Large sized films can be readily produced using the gas phase reaction process. These processing features make the use of a-Si in large sized devices possible. *Fig. 1* shows the plasma CVD apparatus developed and used by Fuji Electric in its production lines.

Excellent photoconductivity and high optical absorp-

Fig. 1 a-Si film deposition apparatus



tion coefficients characterize a-Si as a photoelectric conversion material. The conductivity of a-Si increases by a factor of 10^4 to 10^5 when exposed to sunlight. The absorption coefficient for wavelengths of 500 to 600 nm is greater than that of crystaline silicon an order of magnitude. Therefore, a solar cell can be constructed on a film less than 1 μm thick.

It should be emphasized that the technology implies the possibility of producing new materials such as microcrystalline films. Glow discharge decomposition of SiH_4 under controlled electrical power and gas flow rate yeilds a microcrystalline film in which crystallites of approximately 10 nm diameter are bonded with a-Si. Thus a device in which amorphous and microcrystalline silicon is combined can be produced in a single chamber.(2) A third element (other than silicon and hydrogen) may be introduced in the film structure to give novel characteristics. For example, incorporation of carbon atoms into a-Si results in a band gap greater than that of normal a-Si, while germanium and tin atoms narrow the band gap. It is expected that combinations of these materials will result in new devices with novel functions.

3 SOLAR CELLS FOR HAND-HELD CALCULATORS

Solar cells for hand-held calculators have been designed to maximize the photovoltaic performance of cells under room light. Presently, pocket calculators account for the largest use of such indoor photocells. Game machines and other applications are also possible.

3.1 History

The first commercial a-Si device was the solar cell for hand-held calculators developed in 1980. This development was prompted by the following:

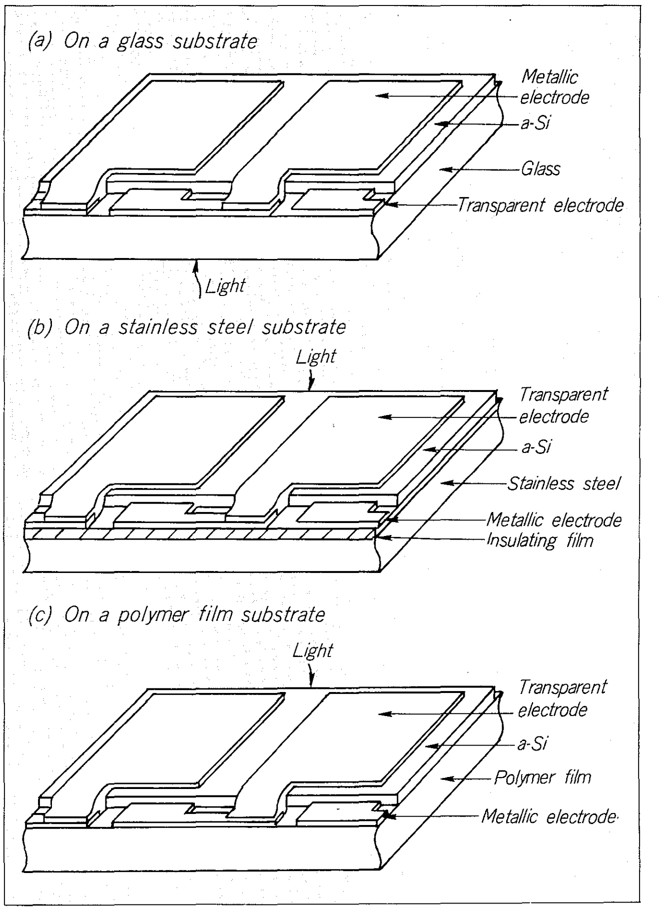
1) The decrease in power consumption of LSIs and liquid crystal displays, which allowed the use of solar cells as a power supply.
2) The fact that calculators can function at light levels required for reading, back-up batteries are not required.
3) The adaptability of *a-Si* solar cell design to the calculator, which contributes to better apperance and to a higher added value of the product.

The first a-Si solar cell was reliatively large in size and did not function at light levels of less than 200 lx. However, the conversion efficiency has drastically been improved in recent years. At this time cells operating at 50 lx are in commercial use. Nearly 50% of the approximately 100 million calculators produced annually are equipped with solar cells.

3.2 Structure

The cells are classified into three categories according to the type of substrate material: glass, stainless steel and polymer film. The glass type is most commonly used; the others are characterized by the flexibility of the substrate. In each type, the cell units, normally four, are connected in series through contacts. Standard operating voltage is set at 1.5 volts. *Fig. 2* shows the three types of construction.

Fig. 2 Structure of a-Si solar cells for indoor use



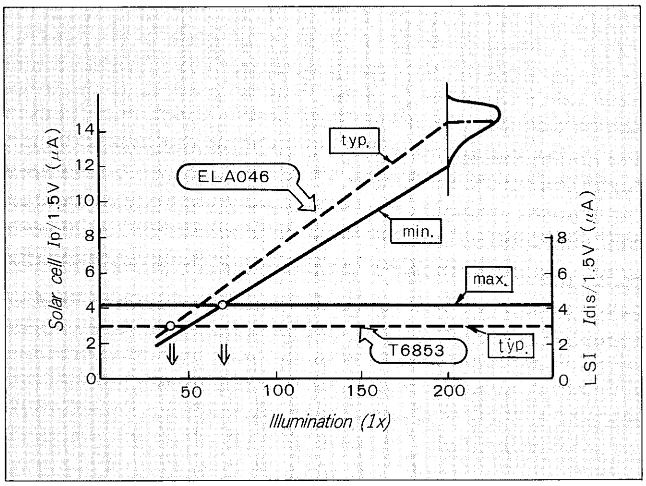
3.3 Characteristics

Specifications of some typical glass-type solar cells for calculators are shown in *Table 1*. The present product line includes many other types, some of which contain more than five units in series. When used as a power supply, the cell should be matched to the LSI, with the power consumption of the LSI as the load. *Fig. 3* shows the design characteristics of the FLA046 solar cell matched to an

Table 1 Output characteristics of a-Si solar cells for indoor use

Type	Output characteristics (under white light, 200 lx)		Outer size (mm)	Number of units in series
	Operating current (μA)	Operating voltage (V)		
ELA056	5.0	1.5	30.7 x 11.0	4
ELA047	6.0	1.5	29.6 x 11.8	4
ELA048	6.5	1.5	41.5 x 9.9	4
ELA045	7.0	1.5	38.0 x 12.4	4
ELA060	8.0	1.5	35.1 x 13.7	4
ELA046	12.0	1.5	55.0 x 13.5	4
ELA049	15.0	1.5	55.0 x 14.5	4

Fig. 3 Typical characteristics of a cell and an LSI used for calculators



T6853 LSI.

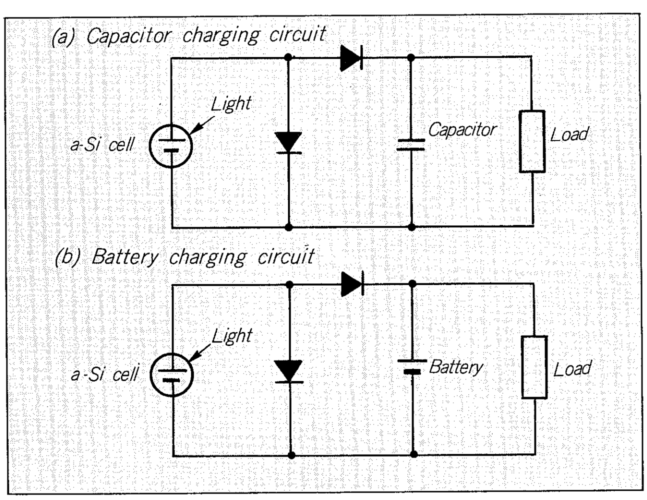
High performance a-Si solar cells which can power a calculator at a light level less than 50 lx, have photoelectric conversion efficiency of nearly 15% under white fluorescent lighting.

4 SOLAR CELLS FOR WATCHES

In recent years a-Si cells for powering watches have seen a gradual increase in demand. In watches, a-Si cells are used to charge secondary batteries (AgO or Ni-Cd cells) or capacitors, as shown in *Fig. 4*. In calculators, the cells are used to drive the LSIs directly.

In developing a-Si cells for watches, Fuji Electric benefited from its experience both in low illumination (cells for calculators) and in high illuminance (large sized cells) technology. Some structural, electrical and design features are presented below.

Fig. 4 Basic charging circuit using a-Si cells for watches



4.1 Structure

Integration of the cell to a watch necessitates a thin, fine-patterned structure. On a 0.4 mm thick glass substrate, a transparent electrode, an a-Si layer with a p-i-n structure, a back-electrode and a protective coating are formed, and the whole structure is confined to a thickness of less than 0.45 mm. Accuracy of pattern alignment higher than 30 μm is attained by use of photolithographic techniques.

4.1 Characteristics

Table 2 lists output characteristics of solar cells for watches. The cell can be charged either indoors, or at a higher rate, outdoors. This feature is the result of the optimal combination of the optical transmittance and resistivity of the transparent electrode, a-Si film thickness, and the pattern design.

Table 2 Output characteristics of a-Si solar cells for watches

Type	Output characteristics [AM1 (100mW/cm^2)]		Outer size
	Operating current (mA) min.	Operating voltage (V)	(mm x mm)
ELB001	0.7	2.3	19.0 x 4.8
ELB002	0.9	2.3	21.5 x 4.4
ELB008	0.3	2.3	9.7 x 4.7
ELB009	1.4	2.3	19.0 x 7.8
ELB014	0.25	2.3	15.0 x 3.0

4.3 Design

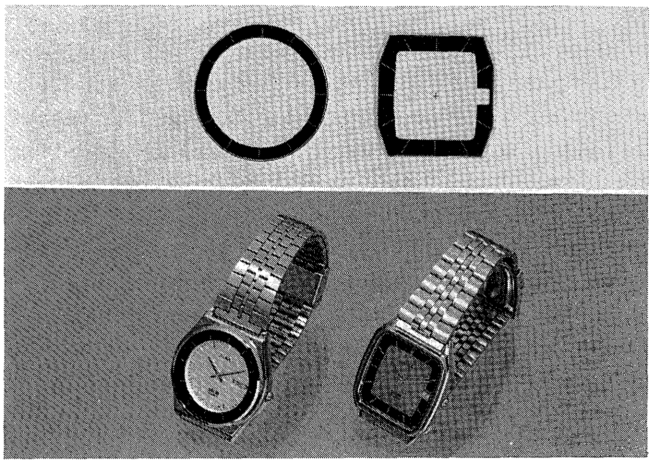
The appearance of the cells is important because of the decorative function of watches. An advantage of a-Si is flexibility in the choice of photolithographic patterns according to watch design. The colar can also be varied, in a limited range, by controlling the thickness of the transparent electrode and a-Si layer.

Recently Fuji Electric began to produce and to supply new types of a-Si:H solar cells for wrist watches shown in *Fig. 5*. They have various shapes suitable to place on the dial of analog watches. Suprisingly the watch has no battery but a capacitor. Electrical energy generated with the a-Si solar cell is stored in the capacitor. The combination of the efficient a-Si solar cell and the efficient capacitor (electric double layer capacitor) drives a C-MOS IC and a step motor in the watch for 50 hours when charged full capacity. The time required for full charge is only 3~4 minutes under the sunlight of fine day.

5 LARGE SIZED SOLAR CELLS FOR OUTDOOR USE

A large sized substrate can easily be coated with an a-Si

Fig. 5 New type of a-Si solor cells (upper) and wrist watches powered by these cells (lower)



layer. This feature was fully utilized in developing the large sized solar cells to be discussed next. These cells are used as outdoor battery chargers, for street lamps and for the power supplies of outdoor clocks.

5.1 Structure

Fig. 6 is a schematic representation of the structure of large sized solar cells. On a glass substrate are stacked a transparent electrode, an a-Si layer in p-i-n configuration and a metallic backed electrode in this order. These elements are arranged in a striped pattern, with the end of the transparent electrode stacked against the metallic electrode of the next stage. In other words, the whole cell consists of a number of unit cells connected in series, each of which possesses an electromotive force with a positive charge at the transparent electrode and a negative charge at the back electrode. A remarkable feature of a-Si solar cells is that this type of series connection is easily constructed on a single substrate and the desired output voltage can be obtained.

5.2 Characteristics

A series or cells have been developed with an output power under sunlight (AM1, 100 mW/cm^2) ranging from 45 mW to 450 mW (see *Table 3*). Modules consisting of

Fig. 6 Structure of the a-Si cell for outdoor use

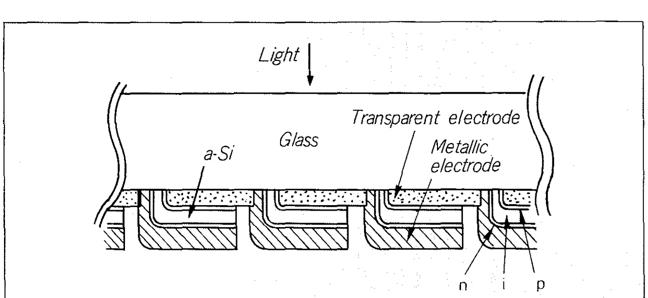
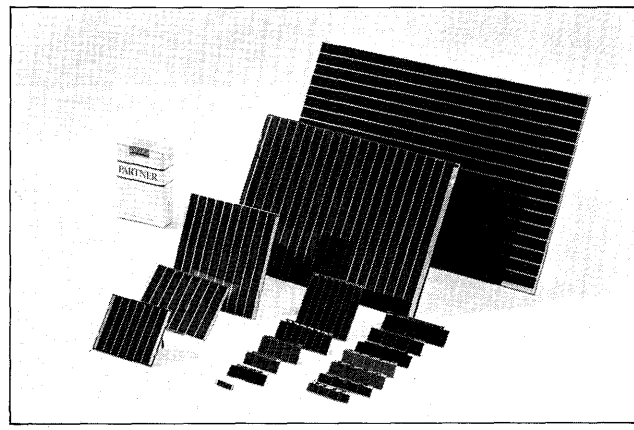


Table 3 Output characteristics of a-Si solar cells for outdoor use

Type	Output characteristics (AM1, typical)		Outer size (mm)
	Operating current (mA)	Operating voltage (V)	
ELB011	10	4.5	53.0 x 25.0
ELB012	20	4.5	53.0 x 50.0
ELB005	40	3.2	65.5 x 53.0
ELB006	100	4.5	100 x 100

Fig. 7 A variety of a-Si solar cells



combinations of these cells can be used to construct a power supply system of approximately 10 W. The establishment of large-sized a-Si film growth techniques and optimum unit design have contributed to the realization of this type of product.[(3), (4)]

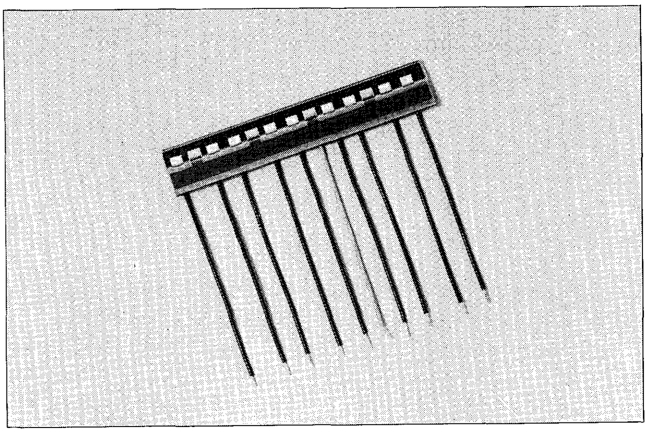
Fig. 7 shows a large sized solar cell for outdoor use and a cell for calculators.

[6] PHOTOSENSORS

Amorphous-Si films can be formed on a large sized substrate in any pattern. They have good photoelectric conversion characteristics. These features make the *a-Si* suitable for daylight sensors because its sensitivity spectrum suitable fordaylight sensors because its sensitivity spectrum is close to that of the human eye. The demand for sensors is rapidly growing thanks to the development of robotics, office automations, and so on.

Fig. 8 shows an *a-Si* photosensor developed to detect defects such as pits, chips and cracks on flat, sheet-like products. Detector units consisting of a-Si film with a p-i-n structure are linearly arranged on a glass substrate. The cell shown in the figure is made up of nine units, 3 by 6 mm in size, and detect defects greater than 2 mm in diameter on a 60 mm wide sheet. For a sheet of greater width, additional units are used. Sensitivity can be improved by reducing the size of the unit. A miniaturized linear image sensor for facsimile, which can detect eight bits per mm, is presently

Fig. 8 A sensor for detection of defects on flat, sheet-like products



under development. This line sensor, comprising 1,728 detector units, can read an A4 size page without the use of a lens system, and thus contributes to decreasing the size of facsimile transmitters considerably.

7 CONCLUSION

The use of a-Si in photoelectric conversion devices was first reported in 1976.[5] In only four years a-Si solar cells for calculators were in commercial production.[1] It was not long before approximately half of all hand-held calculators were powered with a-Si cells. The use of solar cells in calculators is still increasing. In addition, a-Si devices have been developed for other consumer products. All this clearly indicates the fitness of a-Si as an opto-electrical material.

In this paper, we have presented some examples of a-Si devices already on the market. Fuji Electric will continue to further develop new products to meet market demand.

References:

(1) Y. Uchida et al.: Amorphous Silicon Solar Cells, Fuji Electric Review, **27**, 2, pp. 34~40 (1981).
(2) Y. Uchida et al.: Microcrystalline Si: H Film and Its application to Solar Cells, Jpn. J. Appl. Phys., **21**, 9, pp. L586~L588 (1982).
(3) Y. Uchida et al.: Recent Progress in Amorphous Silicon Solar Cells, Fuji Electric Review, **28**, 4, pp. 116~122 (1982).
(4) Y. Uchida et al.: Amorphous Silicon Photovoltaic Modules, J. Electrochem. Soc., **130**, 3, pp. 712~716 (1983).
(5) C.E. Carlson & C.R. Wronski: Amorphous Silicon Solar Cell, Appl. Phys., Lett, **28**, 11, pp. 671~673 (1976).