THE HISTORY OF PHOTOVOLTAICS – A BRIEF HISTORY

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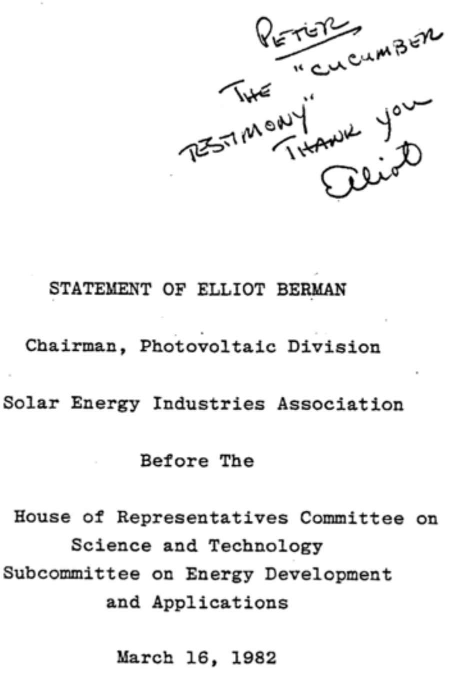
The history of solar energy conversion is normally traced back to A.E Becquerel's paper 'On Electric Effects under the Influence of Solar Radiation' [Comptes Rendues 9, 561 (1859)]. But talk about utilising the energy of the sun for human use goes backeven further. I have here a story about that.

It was my job at the 1982 Solar World Forum of the International Solar Energy Society in Brighton, England, to assess some of the submitted papers. After my technical material, I noted in the publication that our field had fascinated men for many years, and so I quoted from a certain book, the title of which will be revealed later, a description by a visitor to the Academy: "The First Man I saw was of meagre Aspect, with sooty Hands and Face, his Hair and Beard long, ragged and singed in several Places....He had been 8 years upon a project for extracting Sun-Beams out of Cucumbers.... which would warm the air in raw inclement Summers. He told me, that he did not doubt that, in Eight Years more, he should be able to supply the Governor's Gardens with sunshine, at a reasonable Rate; but he complained that his Stock (of cucumbers) was low, and entreated me to give him something as an Encouragement to Ingenuity, especially as this had been a very dear Season for Cucumbers."I gave him a small present ...." It goes on, but this will suffice for us.

Who was this intrepid visitor and what was he visiting ? It was Gulliver, creation of Jonathan Swift, on his imaginary visit to the Academy at Lagado (published in 1792). Now, as this story was part of my report, it was duly published in the Proceedings of the Conference. Next, we come to another conference on solar energy, the 17th Photovoltaic Specialists Conference of May 1984. There, between sessions, I sat down for tea at a table of people some of whom I did not know. I was introduced; and one of the people there exclaimed in disbelief " Are you the Dr Landsberg of the cucumber story?" This man turned out to be Elliot Berman, a distinguished member of the American Solar Energy Industries Association. He proceeded to tell me that he had recently (in 1982) applied for funds to the House of Representatives' Subcommittee on Energy Development and Applications, and explained that at the end of his application he cited the piece from Jonathan Swift's story. "You see, Dr Landsberg, he ended triumphantly, the story is now in the records of the U.S. House of Representatives !"(Fig 1).


PETER
THE "CUCUMBER TESTIMONY"
THANK YOU
Elliot

STATEMENT OF ELLIOT BERMAN

Chairman, Photovoltaic Division

Solar Energy Industries Association

Before The

U.S. House of Representatives Committee on
Science and Technology
Subcommittee on Energy Development
and Applications

March 16, 1982

Fig. 1. Elliot Berman's statement of 1982

Let us now go to science. Key points for the understanding of solar cells are 1. The study of solar radiation and 2. to note that cells are normally solid and so require some knowledge of the solid state. Both topics require understanding beyond school physics. We shall start with the FIRST topic, the radiation from the sun. We show (see Fig 2) the spectrum (strictly the spectral irradiance in kWm^{-2} micrometre^{-1}) as a function of wavelength.

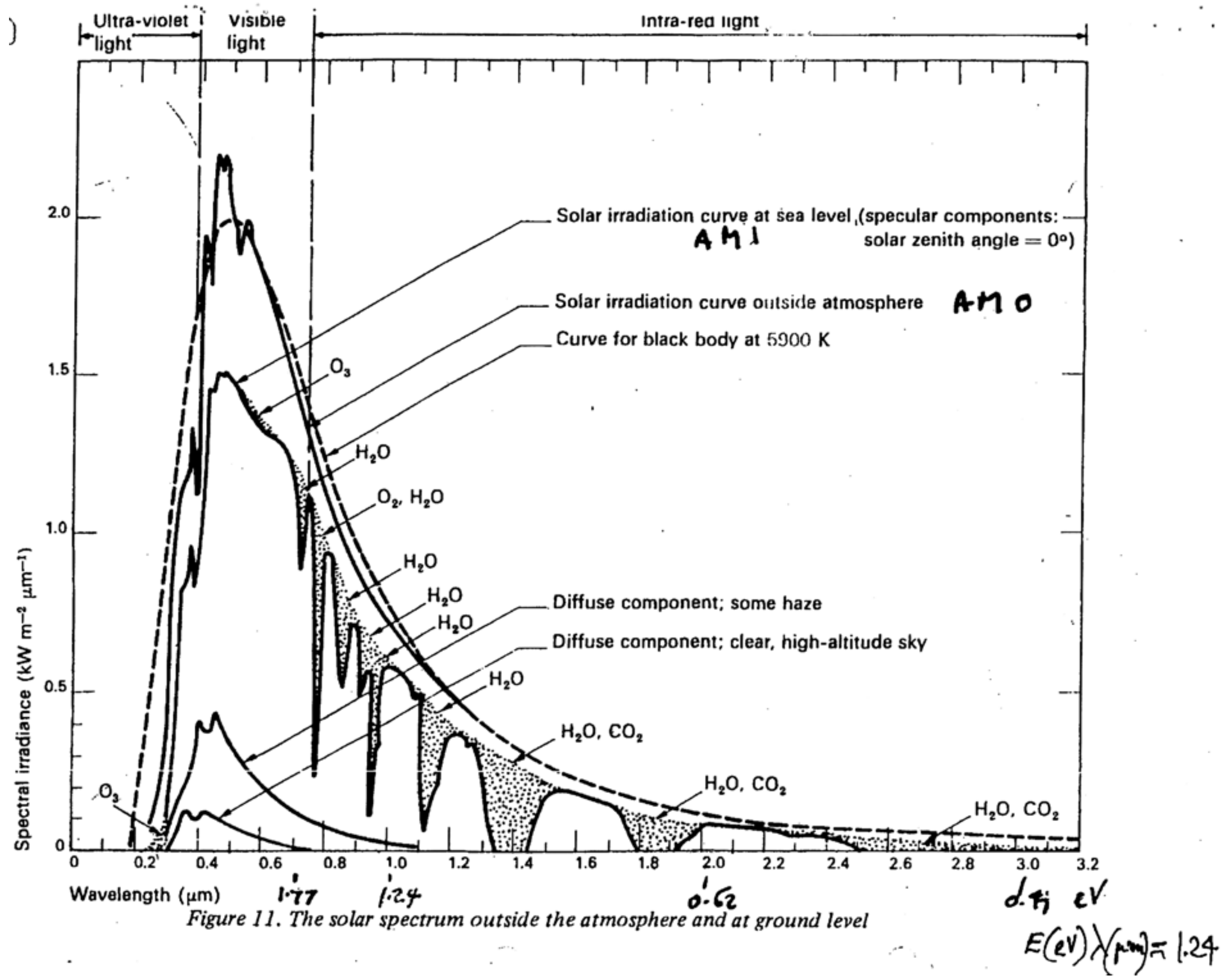


Fig. 2 The solar spectrum outside the atmosphere and at sea level.

There are many dips in the spectrum due to absorption by water vapour, oxygen and other gases. We show not only the normal spectrum but also the 'diffuse' component which has a narrower spread of wavelengths(or frequencies) and contains far less energy. The relatively energetic photons are on the left of the curve (relatively blue, short wavelength) and the relatively energetically weak, or red, photons are on the right-hand side. There is a very important curve as well on this diagram. It refers to a so-called black body of temperature 5900 K, which has a spectrum which closely resembles the solar spectrum just outside the atmosphere. Many calculations can be made in an approximate manner using THIS curve rather than the correct solar curve. In fact, in any consideration of solar energy, the rather simple concept of the "black body" is very helpful: Its energy is simply a constant multiplied by the absolute temperature raised to the fourth power .

The SECOND topic referred to the solid state. As is widely known, the states of possible electronic energies come in bands; when there are two relevant ones, the higher one is called the conduction band, and the lower one is called the valence band. In order that there be equilibrium among the electrons in the bands a certain parameter, called the Fermi level, must lie at the correct height on the energy level scheme. If it is too high, there are too many electrons (and too few holes) for statistical equilibrium; if it lies too low, then there are too many holes and too few electrons for equilibrium.

Imagine next that a p-type and an n-type semiconductor are brought together to make a p-n junctiion. In Fig 3a we see a p-type and in Fig 3b an n-type semiconductor. The low Fermi level on the left shows that there are hardly any electrons in the conduction band; the high Fermi level on the right shows that there are hardly any electron vacancie s (or 'holes') in the valence band. On connecting the two pieces, electrons will therefore flow from the right to the left, and this will set up an electric field: the Fermi level drops with the hole concentration on the left, and rises with the electron concentration on the right. We thus see that the built-in potential difference, shown as V_D in the figure, goes up with doping on both sides. The quantity V_D is called the 'diffusion potential'. The effect of a forward voltage is shown in Fig 3 c: It tends to push electrons from the p-side to the n-side; in the absence of an applied voltage or any external connection, the system is on 'open-circuit', and V_D in Fig 3 b denotes the open-circuit voltage. Of course, it is desirable that it should be reasonably large.

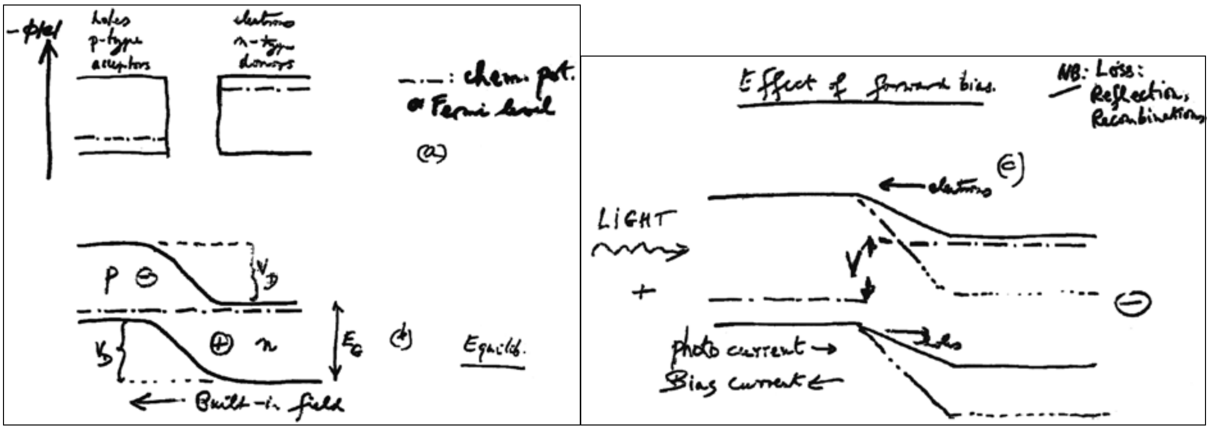


Fig. 3 The origin of a potential energy step in, for example, a p-n junction.
(a) Separated p-type and n-type samples
(b) The same material after contact. Space charge and internal field are also indicated.
(c) A forward voltage lowers the step in the potential energy

We are now able to discuss the energy conversion efficiency of a simple quantum device using black-body radiation. Let us model the device as having only two groups of energy levels at energy E_G apart. Photons with energy greater than E_G excite particles (electrons in our case) from the lower levels to the higher ones. There they sit for a while, bloated with energy, and then they may do something useful. In a solar cell they may go to one electrode to contribute to the light-induced current and voltage. In a biological material the particles could be molecules which, if in an energised state could initiate photosynthesis or the production of new biological material.

In any case, let us suppose that the energetic photons produce particles each able to perform useful work. The energy efficiency is then the ratio of useful power OUT to the incident power. Both these quantities are given by integrals (Figs. 4 and 5); T_S is the temperature of the surroundings and is regarded as variable. One sees that the efficiency is small for a small energy gap E_G, since each useful photon has then a small energy. The efficiency is again small for a large gap as there are only a small number of photons available at these energies. Between these extremes the efficiency goes through a maximum at the reasonable energy gap of order 1 eV. On the other hand, the maximum itself is unrealistically high- solar cells do not normally reach an efficiency of 40% (Fig 4).

I have outlined a simple model for energy conversion by a solar cell. There are many more details which might be added for there are whole books written on our subject. However, I do not wish to confuse the main issues by an excess of detail. I shall therefore pass on to some history, followed by an appreciation of how much solar energy is in fact available.

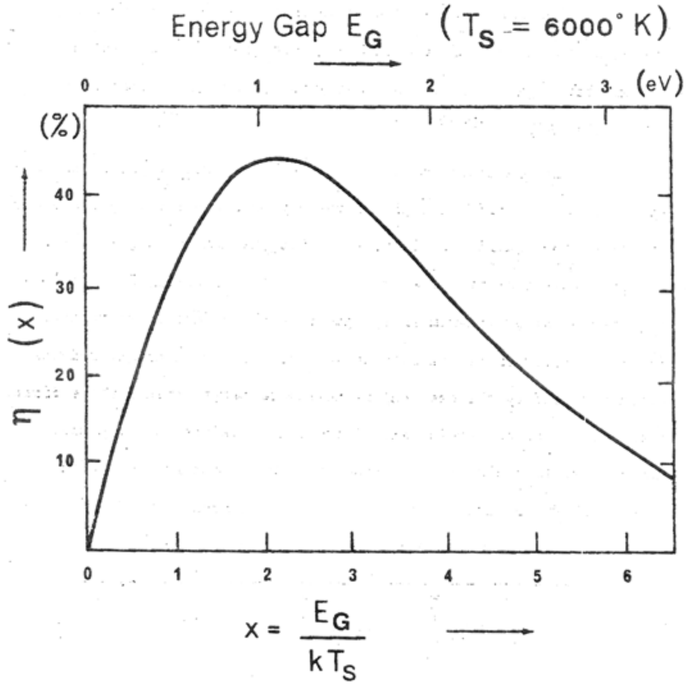


Fig. 4 The energy conversion efficiency for a simple model

$$\eta \equiv \frac{\text{Useful power}}{\text{Incident power}} = \frac{E_G \int_{E_G}^{\infty} \frac{E^2\, dE}{\exp \beta E - 1}}{\int_0^{\infty} \frac{E^3\, dE}{\exp \beta E - 1}} = \frac{x_G \int_{x_G}^{\infty} \frac{x^2\, dx}{\exp x - 1}}{\int_0^{\infty} \frac{x^3\, dx}{\exp x - 1}} \qquad \left(\beta \equiv \frac{1}{kT_S}\right)$$

For maximum of η as a function of $x_G = E_G / kT_S$

$$\int_{x_G}^{\infty} \frac{x^2\, dx}{\exp x - 1} = \frac{x_G^3}{\exp x_G - 1} \qquad \text{Therefore } x_G = 2.17$$

Generally

$$\eta = x_G \int_{x_G}^{\infty} f(x)\, dx \Big/ \int_0^{\infty} x\, f(x)\, dx$$

<u>EFFICIENCY OF 2 - LEVEL DEVICE</u>

Fig .5 The efficiency equation for Fig.4.

. First some historical remarks in three stages. FIRST Stage: In the late 1920ies a physicist born in Germany and who became a US citizen in 1934 filed three patents describing a prototype of what is now known as the field effect transistor, twenty or so years before the work of the famous American Nobel Laureates William Shockley, Walter Brattain and John Bardeen. His widow, Beatrice Lilienfeld, left a considerable sum in 1982 to the American Institute of Physics in her will for the establishment of a major award in her husband's name.(For more details see [1].) Several distinguished scientists received the Julius Edgar Lilienfeld prize over the years: David Mermin (1989), M V Berry (1990),.S W Hawking (1999), R J Birgeneau (2000), L M Krauss (2001), F Wilczek (2003), see Fig. 6, 7.

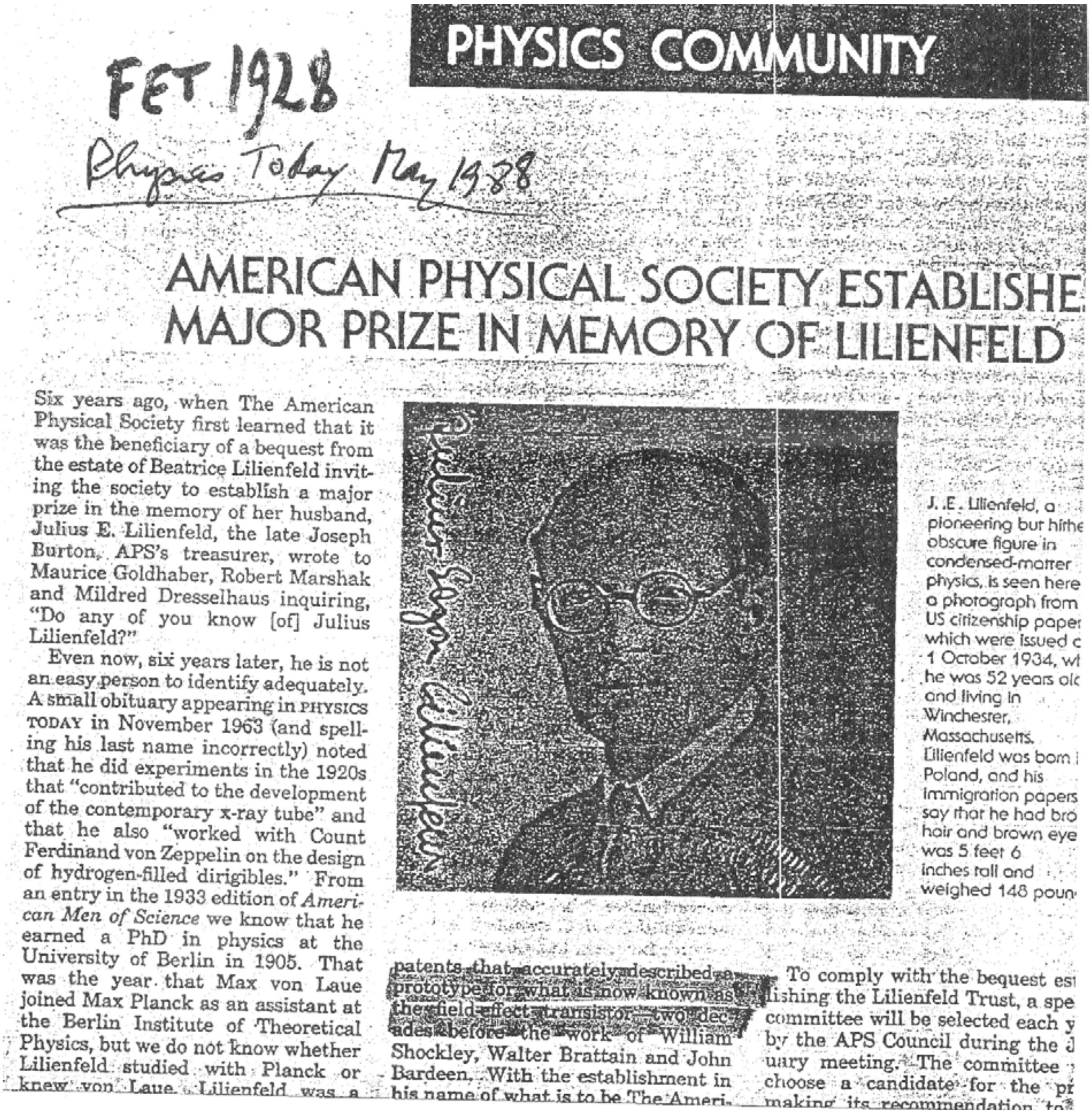
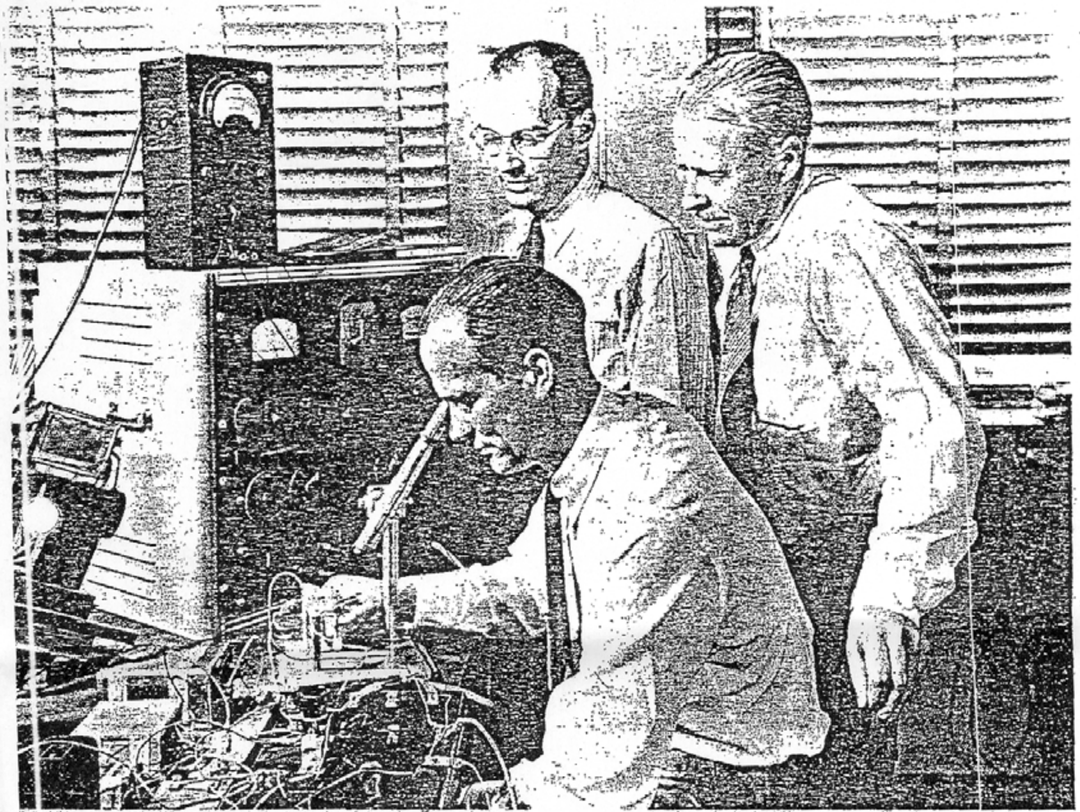


Fig. 6 Julius Lilienfeld (born 1882) from Physics Today, May 1988.

The SECOND stage of historical remarks relates to the award of the Nobel prize for the development of the point-contact transistor to the above mentioned three Americans in 1956. Bardeen went on to be awarded his second Nobel prize in Physics jointly with L N Cooper and J R Schrieffer in 1972 for their explanation of superconductivity. This was not the end of Nobel prizes for this area of work, and we arrive at the THIRD stage: In the year 2000 Physics Nobel prizes were awarded for the integrated circuit [2] (Jack Kilby, formerly of

Texas Instruments and RCA in the USA), and the invention of semiconductor tandem cells or heterostructures (Z Alferov of St Petersburg and Herbert Kroemer of the University of California).



ne ers. In 1947, physicists William Shockley (seated), John Bardeen (left), and Walter H. Brattain of Bell Telephone Laboratories developed pc int-contact transistor—the first solid-state amplifier. The three received the Nobel Prize in physics in 1956.

1948

va to quantify the behavior of electrons in solids had await Erwin Schrödinger's famous quantum-mechani- equation, which the Austrian physicist published in 26. Within the next 10 years eager physicists were ist by the equation, which tied together all the zl solid-state phenomena encountered during the ce ling century.

Wl ile the theoreticians were unraveling the concepts electrons, band theory, and valences, scientists less the matically inclined were experimenting with vari- materials. In the mid-twenties, for example, newly ised solid-state rectifiers could handle far more power n he sensitive cat's whisker. These rectifiers were lt f stacks of copper plates, each oxidized on one espite ignorance of why they operated, manufac- ers turned out the devices in substantial volumes in 1 30s, and even the problem of the stacks' high ward resistance was solved by substituting selenium the oxide.

Then, in the late 1930s, physicists like Nevill F. Mott Eng and, Alexander Sergeevich Davydov in the Soviet on, and Walter Schottky in Germany set out to lai metal-semiconductor rectification. The rectifica- mechanism was generally agreed upon: the semicon- tor material becomes depleted of current carriers at the junction, which creates an effective barrier to equilibrium electron flow across the junction. Application of an electric field that reduces the barrier—a higher potential on the semiconductor side—permits electron flow, while reversal of that field further depletes the semiconductor of carriers, thus heightening the barrier to electron flow.

Many inventors struggled with the notion of a solid-state amplifier. The more common attempts were based on the field-effect principle, most likely because its concept was akin to the grid-control action of vacuum tubes. The first recorded attempt in the United States dates to 1925, when a former professor of physics at the University of Leipzig, Julius E. Lilienfeld, began working on a concept for a solid crystal amplifier.

In Germany, Lilienfeld had assisted Count Ferdinand von Zeppelin in designing the hydrogen-filled dirigible, and he had also experimented with X rays in the early 1920s. After arriving in the U. S., Lilienfeld managed to obtain several patents for an amplifier design based on copper sulfide. He was unable, however, to draw serious industry attention to his work. Most of those who investigated his experiments, conducted in near obscurity in Brooklyn, N. Y., doubted his devices would work at all.

Another patent to an inventor who could not explain

ctrc nics / History of semiconductors

Fig .7 William Shockley, John Bardeen and Walter Brattain of the Bell Telephone Laboratories, here shown in 1947. They received the Nobel prize in Physics in 1956.

I already mentioned tandem cells when I talked here last year, since they offer an example of improving efficiencies by having several materials with decreasing energy gaps in series.

Photons can pass through the first cell, because the energy gap there may be too big for the photon to excite an electron from the lower band. But they may be able to create an electron-hole pair in the NEXT band because its energy gap is smaller. This can in principle be continued down the series of cells, each time with an appropriate cell energy gap. In this way better use can be made of the incident radiation, resulting in a higher efficiency.

In this connection may I mention myself? For in a way I was lucky since I was awarded a research contract by the Clevite Corporation and Shockley Transistors in 1961/2 to investigate the Auger effect and its influence on p-n junction characteristics [3]. It was very exciting to have direct dealings with William Shockley in this way. He was of course a brilliant man, and I had a great deal of respect for him as a scientist; I was rather upset when in his obituaries authors tended to emphasize his reactionary views on race rather than his contributions to science.

Next, consider the paradox that while solar energy falling on desert areas alone, could SUPPLY world energy demand with little pollution if converted at as little as 1% efficiency; it makes IN FACT only a small contribution to world energy consumption. For example, deserts could yield power equivalent to 141 60-watt continuously burning light bulbs per capita, whereas the world energy demand averages out at only 33 such bulbs.This remarkable factor of 4.3 which we have therefore in hand will be eroded of course by increasing living standards and an increasing world population. Using this unit, we can get some rough numbers for energy flows in terms of 60-Watt light bulbs per capita. Using some older data, which may still give a good general idea, it is convenient to refer to an old publication for details [4]. They show that the deserts of the world can IN PRINCIPLE supply the worlds's energy needs for some time to come. Note, incidentally, that the unit of 60 Watt light bulbs per capita, burning continuously, makes the numbers which come out rather easy to handle. In this way one can attain a ather simple overview of the energy balance on earth.

Earth Average Energy Flows

1975 (Pop 4×10^9)	60W bulbs p.c.	J yr^{-1}
Food Consumption	2	1.5×10^{19}
Energy Consumption	33	2.5×10^{20}
Photosynthesis	410	3.1×10^{21}
Solar Energy Incident	396000	3×10^{24}
2000 (Pop 6×10^9)		
Energy Consumption	51	5.8×10^{20}
2020 (Pop 7×10^9)		
Energy Consumption	76	10^{21}

P.T.L. Nature 278, 502 (1979)

Fig. 8. Earth average energy flows

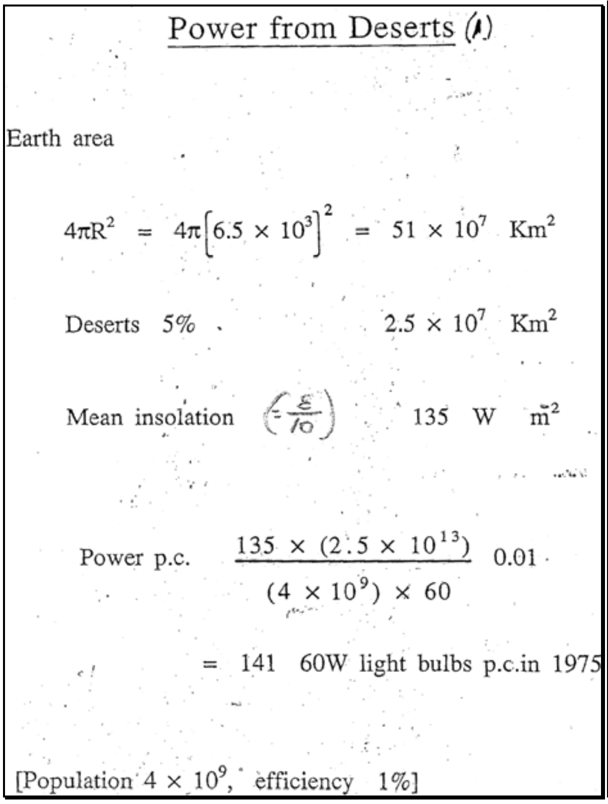


Fig. 9. Power flow from the deserts (1)

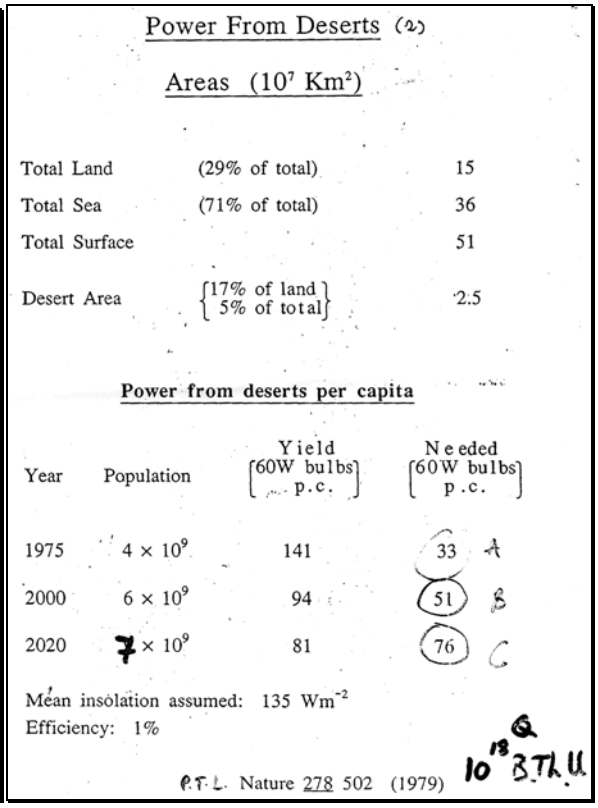


Fig. 10. Power from the deserts (2)

Literature

[1] Physics Today, May 1988

[2] Physics Today, December 2000

[3] D A Evans and P T Landsberg, Recombination statistics for Auger effects with applications to p-n junctions, Solid-State Electronics 6, 169 (1963). See also P T Landsberg, Recombination in Semiconductors (CUP 1991 & 2003), p 130.

[4] P T Landsberg, Energy unit for global use, Nature 278, 502 (1979).