grooved buried contact), and by *R. Swanson* of Stanford University (point contact cell). Light trapping is used now in all kinds of silicon solar cells, and has given a spectacular improvement in conversion efficiency. It enhances the optical path of poorly absorbed red or near-infrared light and allows one to make cells thinner. Thin amorphous silicon cells show less light-induced degradation than thicker ones.

The search for a low band-gap a-Si alloy for solar cells has not yet given conclusive results, as pointed out by *J. Bullot* (Orsay University), since the reproducibility and electronic quality of silicon-germanium alloys are not yet satisfactory. The recent improvement in conversion efficiency of a-Si p-i-n cells is mainly related to the p-doped window layer: microcrystalline a-$Si_{1-x}C_x$:H layers, doping with $B(CH_3)_3$ instead of B_2H_6, and superlattice p-layers. Efficiencies of 10% (active area) for $10 \times 10\ cm^2$ modules were announced by Sanyo (Osaka). *D. Carlson* (Solarex, Newtown, PA) reviewed in-line processing technology for large area a-Si modules. Initial efficiencies of 8% on 1000 cm^2 modules are currently achieved by several American and Japanese companies. Stability of a-Si cells has greatly improved. Light-induced degradation can be reduced to 15% in very thin (0.2 to 0.3 µm) cells.

Polycrystalline cells have seen spectacular progress, too, both in fundamental research (*L. L. Kazmerski*'s (SERI, Denver)talk on the analysis of hydrogen at grain boundaries by scanning tunneling microscopy was one of the highlights of this conference) and on the technological side. *A. Barnett* (University of Delaware) reported efficiencies of over 12.5% with small polycrystalline cells processed on low-cost ceramic substrates.

Non-silicon materials are outsiders in PV technology. In spite of the high price of indium, $CuInSe_2$ continues to attract much attention, especially due to progress in material processing (sputter and spray methods). Stacked a-Si/$CuInSe_2$ cells were described by ARCO. Economic criteria will determine the future of this technology.

It remains an open question whether crystalline, polycrystalline or amorphous silicon will be the leading material for the solar cell technology in the next century. Amorphous silicon seems to have the highest potential for cost reduction. However, this requires large scale plants (well above 1 MW/year), since the initial investment is very high.

The vigorous financial effort of the Commision of the European Comunity and national governments (especially in West Germany) to encourage photovoltaics research and development in Europe has so far been a success. 35 companies exhibited PV modules and systems and showed that photovoltaics is already an industrial reality.

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Research News

Lord Kelvin Updated

William Thompson, better known to science as Lord *Kelvin*, demonstrated theoretically as long ago as 1853 that the rate of temperature change in a cyclically loaded body is directly related to the rate of change of the sum of the principal stresses, if conditions are adiabatic. If a specimen is stressed inhomogeneously, in cyclic fashion, then the distribution of stresses is expressed by a distribution of mean ΔT (relative to the undisturbed temperature of the sample). The ΔT oscillate with the same frequency as the applied cyclic stress. (An increasing tensile stress gives a temperature fall, an increasing stress, a temperature rise.)—Kelvin's principle can be thought of as the thermoelastic analogue of Faraday's principle of electromagnetic induction, established at roughly the same time.

Kelvin's principle has been exploited for some years now to map the distribution of stresses in an inhomogeneously stressed thin flat body—for instance, a sheet containing a hole or a notch—by measuring the time-averaged temperature change at each point by means of a scanning infrared emission camera: the camera is electronically controlled to read ΔT at each test point in synchrony with the frequency of the applied stress. The strategy has been used for non-destructive examination (NDE) of an object's resistance to fatigue damage. Here the cyclic stress is used to modify the state of the material rather than as a mere probe to examine stress distributions. Incipient fracture, or delamination of a fibre-reinforced composite, leads to enhanced local temperature changes, and such damage sites show up in *vibrothermography*—as the technique is sometimes called—long before they can be detected by any other NDE method.[1] The method has been found especially favourable for NDE of fibre-reinforced composites.[1]

However, vibrothermography can do more than provide NDE: given sufficiently sensitive equipment and appropriate theory, the distribution of stresses which would result from an applied steady load can be determined by a ΔT scan with a low-frequency cyclic load which itself is far too small to damage the specimen in any way. A new instrument based on a design by SIRA in England, named

SPATE (for *S*tress *P*attern *A*nalysis by measurement of *T*hermal *E*mission) can be used in this way. (Spatial resolution is 0.25 mm^2 and temperature resolution, 0.001 °C). The infrared signal at each point the specimen at the peak of the stress cycle is averaged over many cycles to achieve an accurate estimate of the stress distribution.

Recent work[2-4] at the Aeronautical Research Laboratory in Melbourne, Australia, has now advanced the technique to new and unexpected level of subtlety. *Machin* et al.[2] found experimentally that, contrary to Kelvin's theory, not only the cyclic stress amplitude but also the mean stress affect the output of the SPATE instrument. Sustained attempts to develop the theory to account for this finding led to an expression[3] in which ΔT is linearly related to the mean stress when measured at the primary frequency, but is modified by a second term with a coefficient proportional to the square of the stress range when measured at the second harmonic (twice the primary frequency). This new theoretical relationship was obtained by taking into account the variation of Young's modulus with temperature, something that *Kelvin* omitted to do. This new analysis offers the prospect of using vibrothermography to separate out oscillating stress amplitudes (which mimic the distribution of stress which would be created by an externally applied load) from a fixed, *residual* stress distribution which exists in the absence of any external load.

In another recent paper,[4] the Australian team has demonstrated that such separation is indeed feasible. For this purpose, the electronic processor which filters out non-primary frequencies has to be by-passed so that any component of thermal response at twice the primary frequency can be separated out. *Wong* and his coworkers[4] prepared an aluminum alloy plate which was plastically loaded to create a predetermined distribution of residual stresses across the plate width. These stresses were also measured with an array of strain gauges cemented to the plate before the plastic loading. The plate was then cyclically loaded, well inside the elastic range, with a non-zero mean load. Use of SPATE with the electronic bypass referred to then allowed the ΔT distribution at each of the two key frequencies to be determined, and from this the residual stress distribution could be calculated. (This was straightforward because the cyclic stress distribution was uniform across the plate). The Figure 1 taken from reference[4] compares the stress distribution obtained in this way, with error bars, with that directly determined by means of the array of strain gauges (solid line). The agreement is very satisfactory.

A few points are not quite clear in the published paper. The ordinate of the graph is simply labelled "residual stress": presumably the sum of the principal stresses is meant. Also, it is not clear whether the use of a non-zero mean load in the cyclic loading regime is essential in order to be able to determine the residual stresses, presumably a non-zero mean load helps in separating out the weak double-frequency term from the background noise.

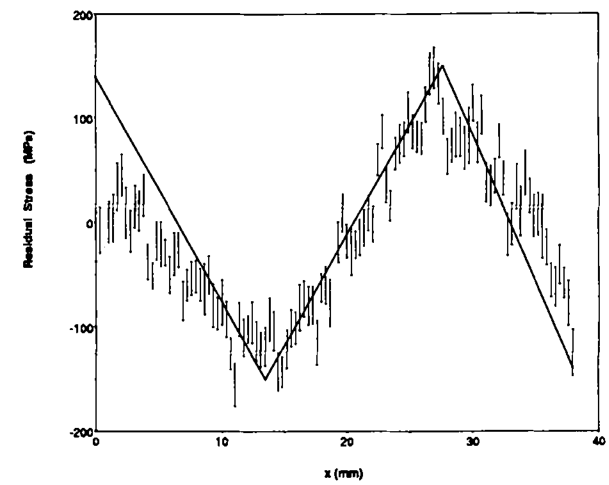

Fig. 1. Residual stress profile for a four-point straightened specimen.

The authors point out that their demonstration was conducted under artificially simple circumstances: the simple rectangular shape of the sample, without holes or other disturbances, meant that the cyclic stress was uniform throughout the specimen. (However, the technique, in this simplified form, could be applied to difficult cases such as that of a glass sheet; the only extant NDE method of estimating residual stresses involves X-ray diffraction and this cannot be used with a non-crystalline material.)—With more realistic specimens of more complex shape, the cyclic stress as well as the residual stress will vary from point to point. To separate out such variables, the sensitivity of SPATE will need to be greatly enhanced, and microstructural features such as grain boundaries and preferred crystallographic orientation of the grains, would also need to be taken into account in these interpretations. Meanwhile, Lord *Kelvin* is well on the way to becoming the most frequently cited nineteenth century physical scientist: his paper on the theory of the instability of liquid jets is already a firm current favourite, and now the even earlier paper on the thermoelastic effect may well join it in its lonely eminence.

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