Ann. Phys. (Berlin) 526, No. 5–6, A41–A45 (2014) / DOI 10.1002/andp.201400806

annalen der physik

THEN & NOW

The Shockley-Queisser paper – A notable example of a scientific sleeping beauty

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In 1961, a paper by William B. Shockley and Hans-Joachim Queisser was published in the Journal of Applied Physics. It discussed a fundamental limit on the conversion of sunlight into electrical current [1]. The "Shockley-Queisser limit" describes the limited efficiency of solar cells on the basis of absorption and re-emission processes. It states that, in single p-n junctions, a maximum of around 30 percent of the sunlight can be converted to electrical current. However, in tandem solar cells with multiple p-n junctions, this limit can be exceeded [2]. The Shockley-Queisser limit has now attained major significance with the steep increase of research in this area and the use of solar energy.

In 1956, Shockley, along with Walter H. Brattain and John Bardeen, was awarded the Nobel Prize for Physics "for their researches on semiconductors and their discovery of the transistor effect". Queisser was one of the founding directors of the Max Planck Institute for Solid State Research in Stuttgart which, through its basic research in the physics of semiconductors, made Germany competitive. The authors of the Shockley-Queisser paper (S&Q paper) give Shockley Transistors in Palo Alto, California as their address. However, that was the location of the company's headquarters and administration. The laboratory in which Hans-Joachim Queisser performed his calculations (with a slide rule) was in neighbouring Mountain View. The primitive apricot barn at 391 South San Antonio Road is considered to be the cradle of the famous Silicon Valley.

The impact of the paper

It is instructive to examine the reception and impact of the S&Q paper more closely, not only from the technical perspective, but also in terms of bibliometrics, the quantitative investigation of scientific publications and their citations. Citations have become an impact indicator in the evaluation of research performance. The resonance or impact of scientific papers on other scientists in the scientific community is frequently measured using the number of citations. It is assumed that the more often a study is cited (at least on statistical average), the more important it is for the further development of a discipline. The database used to determine citations are primarily the citation indexes from Thomson Reuters (Web of Science) [3] and Elsevier (Scopus) [4], as well as Google Scholar [5].

The impact of individual papers ranges from a complete absence of reaction to many hundreds or even thousands of citations. There is significant variation in the different disciplines in line with their different publication and citation cultures. On a global average, chemistry and physics papers were cited around ten times over the last decade [6]. However, these averages mask the fact that the citations are distributed very unevenly across the papers that were investigated: only a small number of papers are cited several hundred times and even fewer a thousand times. A large proportion of papers are only rarely cited over a long period; many are not cited and disappear into the scientific archives without having had any measurable impact.

For the S&Q paper, the situation was thus: its original reception was initially hesitant and, accordingly, citations by colleagues were rare. However, none of the initial citations were critical, and certainly not negative or hostile. Since then, the S&Q paper has become one of the relatively few highly cited papers in its field. Of the total 11,723 physics papers entered in the Web of Science in 1961 (the publication year of the S&Q paper), the S&Q paper ranks 12 in the number of citations up to the present.

The impact over time

For a long time, the S&Q paper seemed to belong to the category of papers that go largely unnoticed, but some 40 years after its publication, this changed: since around 2000, the S&Q paper has been cited

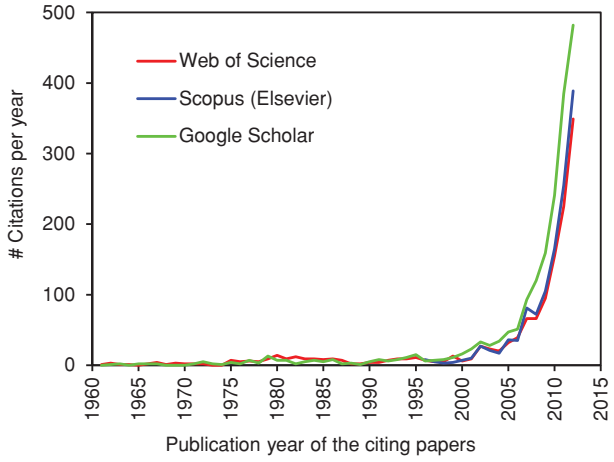

Figure 1 Citation history for the S&Q paper [1] based on three different citation indexes: Web of Science (1,553 citations since 1961), Scopus (1,484 citations since 1996 – earlier citations are currently not included in Scopus) and Google Scholar (3,900 citations since 1961). Date of search: Aug. 10 2013.

increasingly often, and has now amassed between 1,500 and 3,900 citations, depending on the database. This is an unusually high impact, combined with an unusual pattern of impact over time. Citations of a typical paper usually develop very differently: other researchers take note of it in the year of its publication or in the following year, and the citations rapidly rise. The citation rate (citations per year) in chemistry and physics, for example, peaks after about three years. After that the cited papers are displaced by new ones and their impact recedes. The terms "ageing" and "half-life" are used in the context of scientific literature.

This is, however, the general development of citation history averaged over many papers. The impact of papers unfolds individually for each one and often shows significant deviation from the general pattern. The S&Q paper is one of those rare publications which deviates particularly widely. Figure 1 shows the citation history for the S&Q paper since its publication.

The papers citing the S&Q paper are assigned to very different Web of Science subject categories (chemistry, physics, materials science, engineering science, energy research, etc.). They are oriented toward basic research, but also toward application and technology. The different citation figures from the different indexes are mainly the result of the different extents to which the technology literature is recorded. As Google Scholar is the best for recording the field of technology, which is very important for the research field under investigation, it has the highest citation numbers.

In the case of papers that do not attract significant notice until decades after their publication such as the S&Q paper, one refers to "slow reception" or "delayed recognition"; these papers are called the "sleeping beauties of science": "A 'Sleeping Beauty in Science' is a publication that goes unnoticed ('sleeps') for a long time and then, almost suddenly, attracts a lot of attention ('is awakened by a prince')" [7]. Given the long time of delayed recognition and the unusually pronounced late impact, this definition fits the S&Q paper perfectly.

Why so late?

Like many other papers that attained major significance later on and, consequently, were then frequently cited, the S&Q paper was initially not well received [8, 9]. This was a bitter blow for Shockley, who advocated support for top-class research (similar to the discussion surrounding scientific excellence today) and who (with some justification) regarded himself as a top-class researcher. Hans-Joachim Queisser commented on the rejection of the first version [10]:

> "The rejection of the first version of our manuscript was really impolite and humiliating; that's why Shockley was so incredibly angry. It was said that our approach was not new, but a rehash! (...) Shockley was a patriot, and marked by the rivalry with Germany during WWII (dangerously successful submarines – he worked for the Pentagon in this field, he invented the term "operations research"). For Shockley, the strong competition from the Soviet Union, the arch-enemy, meant that the USA should focus more on the quality of research and development (quite simply, the elite!)."

And what are the reasons for the unusual renaissance of individual papers? The bibliometric perspective offers some clues: several papers receiving delayed recognition are cited more after another highly cited paper or a prominent author has drawn attention to them – the equivalent of the prince who wakes Sleeping Beauty. An investigation of the impact of the papers citing the S&Q paper reveals that the most

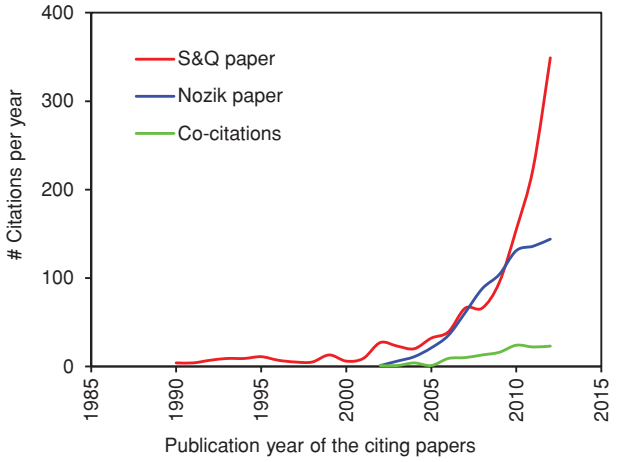

Figure 2 Citation history for the S&Q paper [1] compared with that of the Nozik paper [11] and the co-citations based on the Web of Science.

highly cited papers appeared around 2000. One of these papers citing the S&Q paper is a conference item from A.J. Nozik, which was published in Physica E in 2002 [11] and has so far received 823 citations. The conference took place before that, in 2001, at the Max Planck Institute for the Physics of Complex Systems in Dresden.

This suggests that it was primarily this paper which directed the attention of the scientific community to the S&Q paper and included it in the citation network of current publications. This assumption is confirmed by a comparison of the citation history of the S&Q paper with that of the Nozik paper, and also takes into account the respectable number of 130 co-citations (both papers cited by the same citing paper), as shown in figure 2. However, other prominent citing papers or scientists presumably also contributed to making the S&Q paper better known: from 1980, the citation rate rose briefly several times to above 10 citations per year, and in 2002, when the Nozik paper had just been published, it was 27, but then fell again.

Once a minimum level of attention has been achieved, the citation rate can accelerate, particularly if the research subject in question has become popular and the number of potential citing researchers has increased commensurately with the higher number of researchers in the same area. Figure 3 shows the citation history of the S&Q paper compared with the growth of solar cells and photovoltaics as an area of research since 1960. This was compiled with a title search on the words "solar cell(s)" and "photovoltaic(s)" in the Web of Science (it is not possible to search in abstract texts in the Web of Science prior to 1991). The incomplete compilation of publications in this research field using only words in the title is not expected to have an implication on the structure of the time curve.

As figure 3 shows, the citations of the S&Q paper developed synchronously with the rapidly growing solar cell and photovoltaic research area and its publication output. However, the rapid growth of scientific literature overall since around 1960 must be taken into account when considering time curves of this nature. For example, only 2 per cent of the physics literature of the entire 20th century was published before 1950. The era of Big Science, which is characterised by a steep rise in the publication rate which continues to the present day, started with the "sputnik shock" in 1957 [12], increasing the probability that an individual paper would be cited.

The quantitative method of bibliometrics is not intended to replace assessment of research performance by experts in the same discipline, but to support it; similarly, an individual paper benefits much from an expert

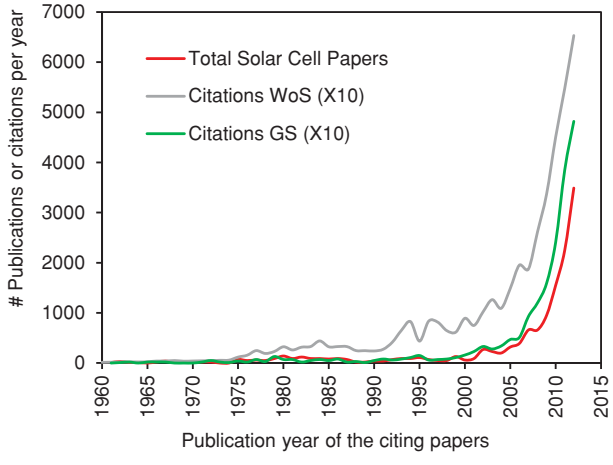

Figure 3 The citation history of the S&Q paper [1] against the growth of research on solar cells and photovoltaics since 1960. To aid the comparison, the citation figures from the Web of Science (WoS) and Google Scholar (GS) were multiplied by 10 (X10).

view. The question of why recognition of the S&Q paper was delayed is therefore best answered by Hans-Joachim Queisser himself [10]:

> "Why was no notice initially taken of the S&Q paper? Our claim that GaAs would make a good solar cell as a semiconductor with direct optical junctions was contrary to the views of RCA and other companies on the east coast of the USA. It was only when the IBM laboratories discovered that one could avoid the extremely high surface recombination of the GaAs charge carriers with a transparent cover layer that this putative deficiency was eliminated; the prediction was correct! There were two important omissions in our manuscript: Surface recombination and a discussion of a possible improvement through photon concentration (for example with a condenser lens). I discussed this years later with Shockley. Apart from that, we were not popular authors in 1961 or thereabouts. Shockley was seen as a sort of erratic defector from Bell Labs and I was a German (it was the time of the Eichmann trial) and we were not exactly shining examples! (...) I was never particularly bothered by this repudiation and the generally negative reception of my presentation at the Am Phys Soc Spring Meeting in Cleveland because there were so many new and important issues surrounding silicon and, last but not least, I was convinced of our very fundamental approach with Planck functions."

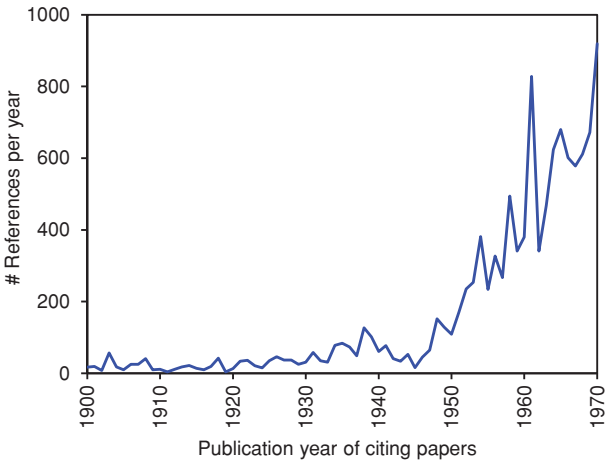

Figure 4 Annual distribution of cited references in publications of research on solar cells and photovoltaics published since 2010 and based on the Web of Science. Date of search: Feb. 07 2013.

Significance in the research area

The S&Q paper offers another interesting bibliometric perspective: instead of asking when and how often it was cited, one can also ask what value it has in relation to all the earlier papers cited by papers in the same research area. This question can be answered with a bibliometric method which, in analogy to traditional spectroscopy, is called "Reference Publication Year Spectroscopy" (RPYS) [13].

An analysis of the publication years of the papers cited by all the papers in the research area shows that earlier publication years are not equally represented, but that some years occur particularly frequently among the references. These early years are more differentiated the more distant they are, and appear in the distribution curve of the reference publication years as pronounced peaks. If one now establishes which actual papers these publication years are based on, one can see that, as a rule, they are single early works which were relatively highly cited. These frequently cited papers, usually few in number, are clearly of special significance to the research field in question and often represent its historical roots.

For applying the RPYS analysis, all cited references have been selected from the papers on solar cells and photovoltaics published since 2010 and covered by the Web of Science (n = 19,396). Figure 4 shows the distribution of the number of the references across their publication years within the time period 1900 to 1970. According to Figure 4, there is a pronounced peak in the reference publication year 1961. Further analysis shows that almost half of the references for 1961 which have been cited by solar cell or photovoltaic papers since 2010 can be assigned to the S&Q paper. This illustrates clearly and quantitatively the high significance of the S&Q paper for current research in its area.

Discussion

The history of the S&Q paper gives rise to a number of questions of fundamental significance in terms of the reception of scientific

papers and the use of citations to measure research performance. Why are some papers cited more frequently only decades later? How likely is delayed recognition? What does that mean for the evaluation of more recent papers and younger researchers?

The complicated nature of scientific progress in the interplay of theory and experiment means that scientists respond critically to new ideas. They first need to become accustomed to them, and then accept them only gradually [8, 9]. At the end also scientists are only human and at the mercy of the *zeitgeist*. On the other hand, ideas which are ahead of their time are stored up for future use. They are ignored, rather than genuinely dismissed, by researchers because no one can make any use of them at the time of their publication.

A number of bibliometric studies have shown that the probability that an initially inconspicuous paper will later attract a lot of attention is very low: in 10,000 papers there is barely one which was initially not or rarely cited and then later went on to receive an unusual amount of notice [7]. Papers with such an extreme resonance history (a long period of quiet and then such high impact later on), like the S&Q paper, are even rarer. These examples therefore cannot be an excuse for a lack of impact.

Seen against the totality of papers, publications such as the S&Q paper are only isolated cases, but not in relation to the small group of innovative papers which have a significant influence on scientific progress. The research process seems to be defined by relatively few papers [14]. In essence, these are not classic pieces of science which are no longer cited explicitly; rather, their familiarity is assumed (a phenomenon which the sociologist Robert Merton calls "obliteration by incorporation") [15].

The fact that even particularly innovative papers are not necessarily immediately identifiable by their impact also affects the now standard practice of measuring research performance on the basis of citations: as a rule, in order to be up-to-date, short periods are chosen, such as the preceding three years. Such new papers (particularly those appearing toward the end of this window) have hardly any chance to develop an impact. However, this gives rise to the danger that a work of crucial significance might be overlooked while the "rush jobs" are rewarded instead – this would make research evaluation counterproductive.

Acknowledgment. The author thanks Hans-Joachim Queisser for valuable advice and informative comments.

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