Volker Lehmann: An Unconventional Scientist

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It is generally known that Volker Lehmann has made numerous important contributions to the science and technology of the various forms of porous silicon. Less well known is that he started his education in the world of art and that he kept this interest alive, even after a professional career in engineering, materials science, physics and electrochemistry. In addition he was an athlete, enjoying all kinds of sports and physical challenges. The paper will be based upon the personal experience of the authors who worked directly with Volker Lehmann or in related fields of research for over two decades.

Introduction

The authors (U. G. and H. F. for short in the following) had the privilege to know and to work with Volker Lehmann for more than twenty years. As it turned out the two most cited publications of Volker Lehmann (1, 2) are also the most cited papers of the present authors showing the close intertwining of the respective research outputs. The purpose of this presentation is not to give an exhaustive overview of his life and scientific work but rather to highlight a few typical aspects and examples of his personality and his life as a scientist; touching also his way of doing research and combining science with art and sports. This presentation is a substantially enlarged version of a recent article in memory of Volker Lehmann by the present authors (3). The article will be structured along his CV with specific examples of his research accomplishments picked out to highlight his style of research and life in general. Sometimes less emphasis will be put on the science and more on the stories around his research and on his personality.

From Birth to Ph. D.

Volker Lehmann was born in December 1959 in Southern Germany in the city of Ulm. From 1976 – 1983 he studied Electrical Engineering at the RWTH Aachen, one of the best German universities devoted to engineering. In the spring of 1982 he did part of the required industrial internship at the then newly established "Solar" department of Siemens Central Research in Munich, Germany. Here he worked for one of the authors (H. F.) who introduced him to Si electrochemistry. The task was to assess the "solar cell quality" of various pieces of oddly shaped Si that were obtained in many novel and unusual ways (e.g. by sintering of Si powder, by melt spinning, or by coating carbon fiber nets with liquid Si) and it was decided to do this by measuring the cathodic photo current of the typically p-type samples via a solid-liquid junction. Everything was new and untried, calling for a "quick and dirty" approach. Volker Lehmann was perfectly suited for this kind of work. Already as an intern he quickly mastered the necessary background in the materials science of silicon and combined it with his training as an engineer and his uncanny ability to build complex machinery from various debris found in any lab. This first encounter with the electrochemistry of silicon as an undergraduate student proved to be decisive for his future research career. He would very successfully stay in this area of research with a passion for a hands-on approach and creative solutions for the rest of his professional life. Based on his positive internship experience, he returned to Siemens Central Research for doing his diploma thesis under the guidance of H. F. His thesis was well received at the University and lead to his first publication in the area of silicon electrochemistry, entitled “A high-speed characterization technique for solar silicon”, unfortunately in a somewhat obscure proceedings (4).

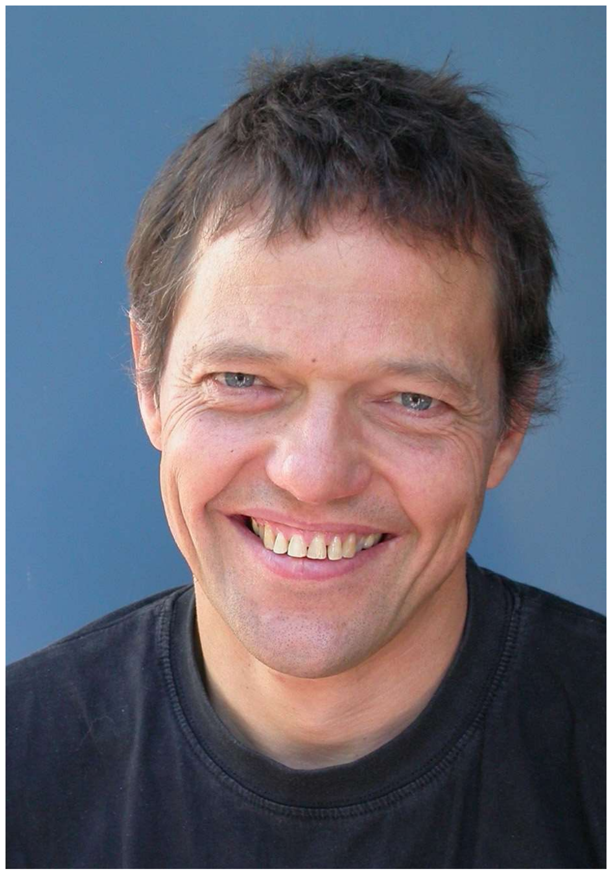
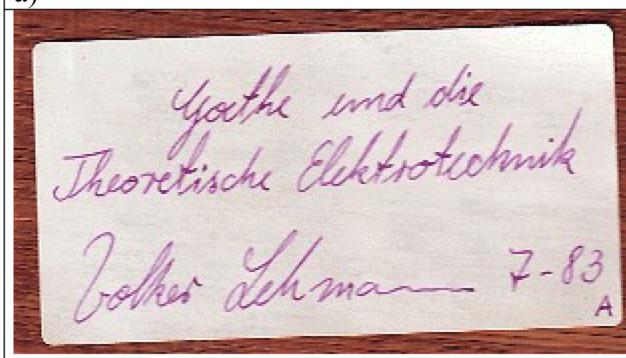


Figure 1. Volker Lehmann

After an interruption of his education necessitated by compulsory civil service (in lieu of military service) he came back to Siemens in the summer of 1985 for a Ph. D. in physics, again under the direct supervision of H.F. but now in association with the University of Erlangen-Nürnberg (Prof. Helbig). Interestingly enough, Volker Lehmann decided to go for a Ph. D. in physics only after his application to the Munich School of Arts had been turned down. All his life he did not only like science and engineering but he also loved to produce works of art himself. Throughout his career he created pictures, lithographies, sculptures, and so on – every technique was of artistic interest to him. Figs. 2 and 3 give some impressions of his early art.

a)



b)

Figure 2. a) Goethe und die Theoretische Elektrotechnik (Goethe and the theory of electrical engineering) by Volker Lehmann, 1983.
62 cm x 62 cm; metal foil from the necks of wine bottles over wood relief.

b) Proud signature on the back (first time he sold a piece of art).

Whatever the artistic value of the piece in Fig. 2 might be, Volker Lehmann met the most common definition for a professional artist: he actually sold that piece - to H. F. in 1983 for about € 500. The craftsmanship and the originality are certainly impeccable. As with most of his art (and to some extent science), one needs to take a second and third look to grasp the meaning and the details. While the piece appears to be just a symphony of letters, it actually carries meaning. Just start to read from the top left to the bottom right (counting the big "a" twice) and you find the sentence "Grau ist alle Theorie" (gray are all theories), which, as all literate Germans will know, is straight from Goethe's "Faust I", and explains not only the title of the piece but also Volker Lehmann's attitude to just theory. The quote goes on as follows: "the verdant tree of Life is green alone". The tree of life, symbolized by the grapevine and its time-honored bottled product, is also found in this piece: many metal wrappers from around the neck of wine bottles supplied the essential material.

Remarkably, any new technique he tried came out rather perfect from the very beginning. Figure 3 shows his first lithography, clearly influenced by Escher; technically perfect and artistically thought provoking, especially for those who feel that the pen in the end will be mightier than the sword.

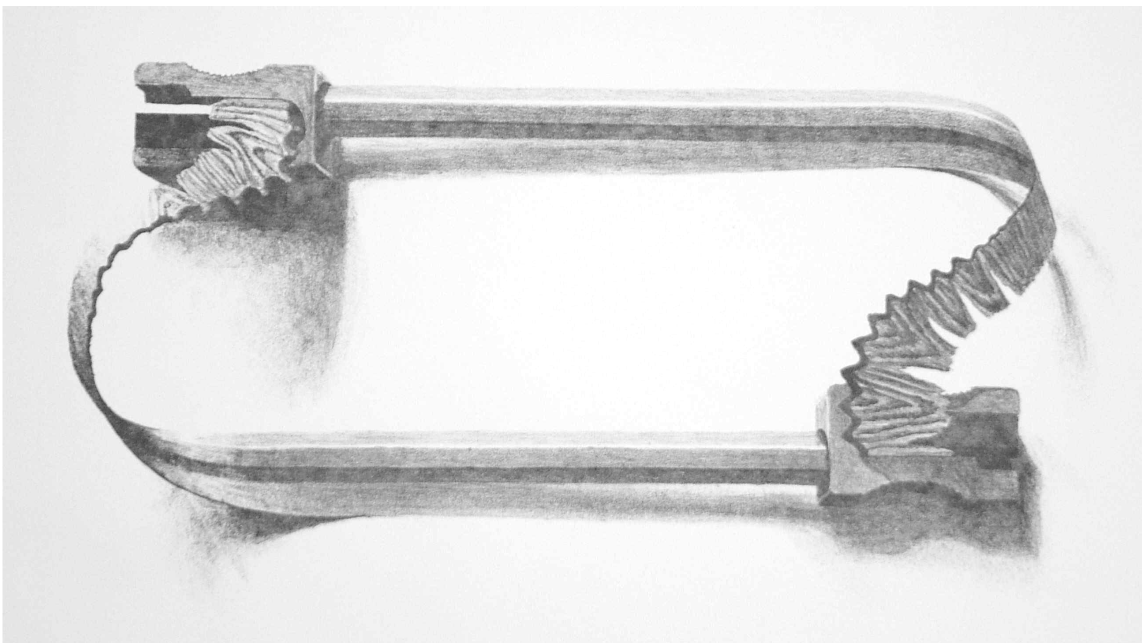


Figure 3. First attempt at lithography (here: printing from a cut flat stone).

After H. F. lend him an old book about "Perpetuum Mobiles" with illustrations of all the (needless to say: wrong) principles and designs that had come up through the centuries, he took that subject close to his heart and started to combine artistry and high-level engineering. Beautifully crafted and artful "Perpetuum Mobiles" emerged from his studio over many years – and they all worked! It took longer and longer, even for his scientifically and technically well trained colleagues and friends, to figure out where the energy was actually coming from, and where the tiny battery was hidden.

In his art, still found in many homes and offices, he lives on just as much as in his scientific contributions. But what was the loss to the artists' community has been the gain for materials science. In his research work for his Ph. D., which he defended in 1988, he put down the foundation for his successful scientific career.

Initially Volker extended his diploma work, dealing with ways for the electrochemical characterization of electronic properties of silicon. This lead to his first major discovery: the "ELYMAT" (ELectrolYtical MetAl Tracer) principle for lifetime mapping in silicon. In 1988 this lead to his second publication entitled "Minority-carrier diffusion length mapping in silicon wafers using a Si-electrolyte-contact", now suitably published in the Journal of the Electrochemical Society (5). Of course, working in the research department of a company, he filed a patent before publishing together with H. F. in 1987. The technique was licensed and produced some (little) money. It is still used, in particular for multi-crystalline solar Si, because it gives the best results and thus is the reference for other methods.

While originally the major interest was in measuring the cathodic photocurrent in p-type Si with frontside illumination (fsi) or, in the case of the ELYMAT, with backside illumination (bsi), his interest shifted gradually to basic questions of Si electrochemistry and to the peculiarities of n-type Si. The formation of what now is called "microporous Si" was of particular interest, and a lot of often quite involved experiments were done (e.g. Rutherford backscattering) and painstakingly written down in his famous Lab books. But no clear picture emerged, and no publications resulted from this early work.

With regard to n-type Si it was already clear that photocurrents etched these samples and that the structures obtained contained a lot of information about minority carriers (4). One day, however, something unexpected happened: after some anodic processing under fsi conditions, the piece of n-type Si under investigation came out looking pitch-black. The SEM quickly showed why (Fig. 4).

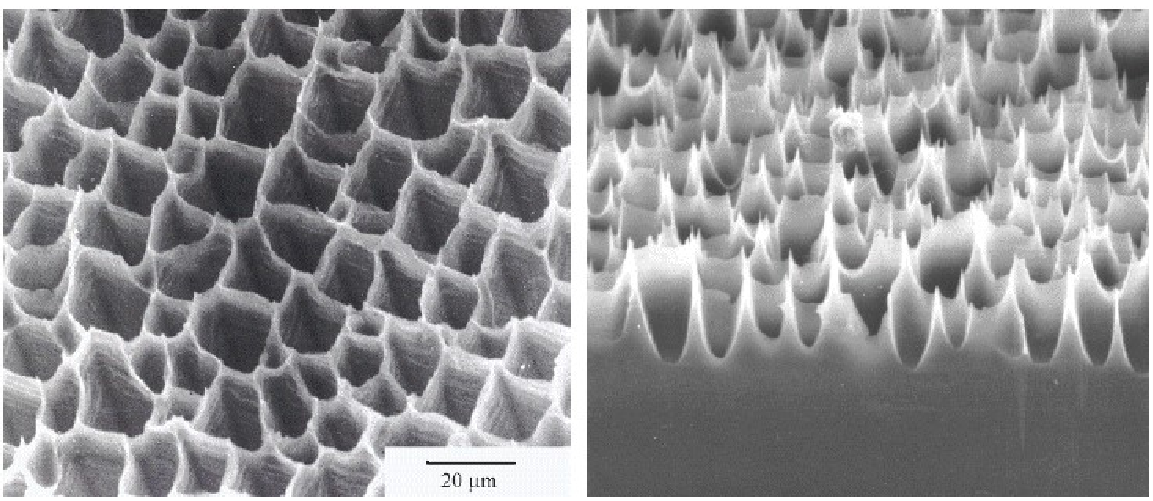


Figure 4. The structures ("fsi macropores") that caused the discovery of deep bsi macropores.

The astonishingly black surface triggered Volker's first patent in 1983 – a method to make cell-like structures for applications in solar cells and catalysts. The patent has long since expired, but the idea seems to get rediscovered every now and then. The big question of course was why such a structure forms in the first place, and the possible answer was because the bend space charge region around accidentally formed tips would capture holes, leading to a preferential growth of the tip. This lead to the prediction that backside illumination should promote "trench" growth, in particular if defined nucleation sites would be provided by lithography. Since H. F. (and thus Volker Lehmann, too) had meanwhile switched to microelectronic memory (DRAM) development, suitable samples from "trench capacitor" development were easy to come by, and the very first experiment in this direction produced the very first deep macropores in lightly doped n-type Si under backside illumination as reported in (1). Note that the microelectronic community for some undisclosed reason likes to misname things: trench instead of hole or pore, wafer fab instead of chip fab, and so on. The title of ref. (1) “Formation mechanism and properties of electrochemically etched trenches in n-type silicon” bears witness to this oddity. A long series of publications and of patents resulted from his work, establishing him early on as a leading researcher in the field of electrochemistry of silicon.

Doing research together with Volker during these times was fun and challenging. He held his own views of things and was not given to accept any scientific (or other) statement if he wasn’t convinced of the truth himself. Just to do some experiment because his advisor told him so was not a good enough reason to march to the lab. However, whenever there was a difference of opinion, wagering a bet (usually for a case of beer) could to the trick. As an example, the IV characteristics for the illuminated case in Fig. 3.2 of his book (10) were the result of such a bet (and they are mentioned here because the topic addressed in these curves would bear some more investigation).

His athletic side, combined with an acute sense for killing two birds with one stone showed in the following anecdote: As a good friend he helped H. F. moving all and sundry to a new house and volunteered to do the laundry room in the basement. How not-so-tall Volker managed to bring a heavy washing machine etc. down a narrow staircase all by himself was not clear to those (= most) of us with less well developed athletic skills but neatly shows that he looked for and accepted challenges. That he used the opportunity to do his whole (bachelor) laundry on the side just showed his knack for making the best out of any situation.

Postdoc Time at Duke University

After finishing his Ph. D. Volker Lehmann joined one of the authors (U. G.) as a postdoc in the Department of Materials Science and Engineering at Duke University in North Carolina with his then girlfriend and later wife Judith. The paths of Volker Lehmann and U. G. had crossed earlier when U. G. had worked for a short period at Siemens Central Research in Munich as well, before accepting an offer as Professor of Materials Science at Duke University. In fact, U. G. came across the name of Volker Lehmann when he visited the house of H. F. and inquired about the special piece of art hanging there that is shown in Fig. 2.

At Duke only a one year postdoc position was waiting for him, whereas Siemens Corporation had offered him a “real job” and indicated that in one year’s time such an opportunity would most likely not be available anymore. It was typical for Volker Lehmann that he made his decision based on his love and interest for research and new aspects in life and that he took the risk of possibly not getting a job when going back to Germany. As it turned out later, Siemens Corporation was still interested in hiring him after the one year postdoc period had passed.

His main job as a postdoc was to work on silicon wafer bonding and pushing the area of silicon-on-insulator (SOI) wafer fabrication, involving electrochemistry for etching back one of the bonded wafers down to the desired thin SOI layers. He wrote a number of well-cited papers in this area (6, 7). However, his scientific heart was still pounding for the electrochemistry of silicon. Therefore, parallel to the work on wafer bonding, he pursued discussions on the experiments on microporous silicon he had performed while still in Munich and that he had never published since they appeared to make no sense. The puzzling question was mainly which effect could possibly lead to the passivation of (2 – 5) nm silicon structures against further electrochemical etching. U. G. was just teaching a course in which quantum size effects played an essential role and these happened typically in this range of sizes. After some discussions a simplified back-of-the-envelope theoretical estimate showed that such sizes should indeed lead to a substantial increase in the bandgap of silicon, which would then explain the passivation by a quantum mechanical confinement effect. Obviously, such an increase in the bandgap of microporous silicon as compared to normal bulk crystalline silicon should be optically observable. Volker Lehmann immediately set out to do these experiments, “borrowing” the missing optical equipment from the nearby department of Physics. Within a very short time his experiments clearly showed the expected increase in the bandgap of porous silicon and consequently all his earlier experiments performed in Munich suddenly made sense. Lehmann later on sketched the basic effect of quantum confinement controlled etching as shown in Fig. 5.

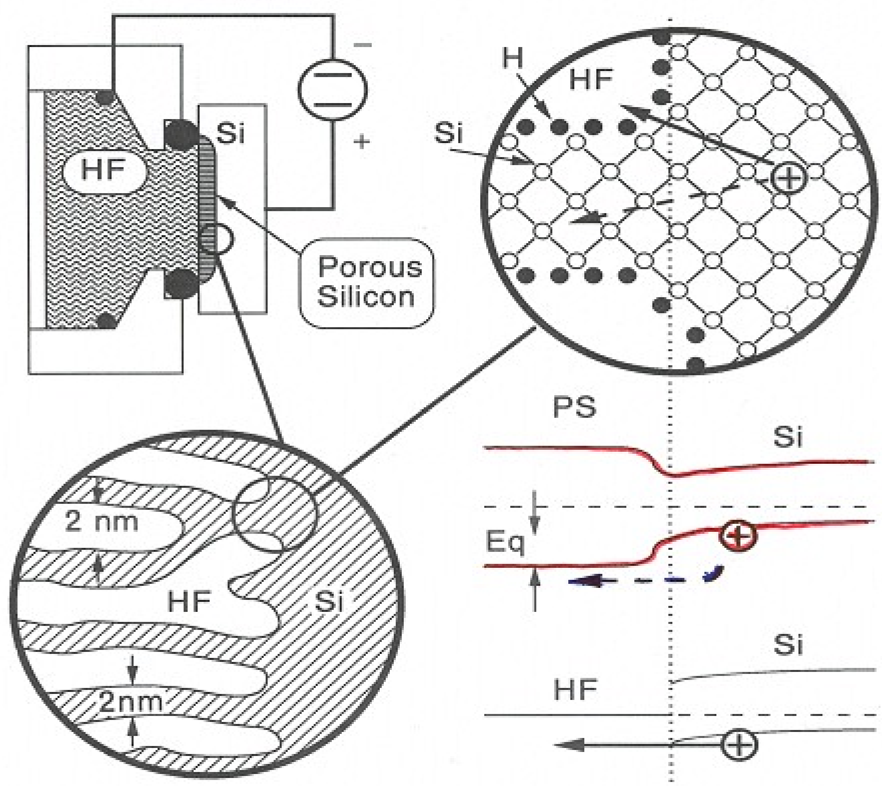
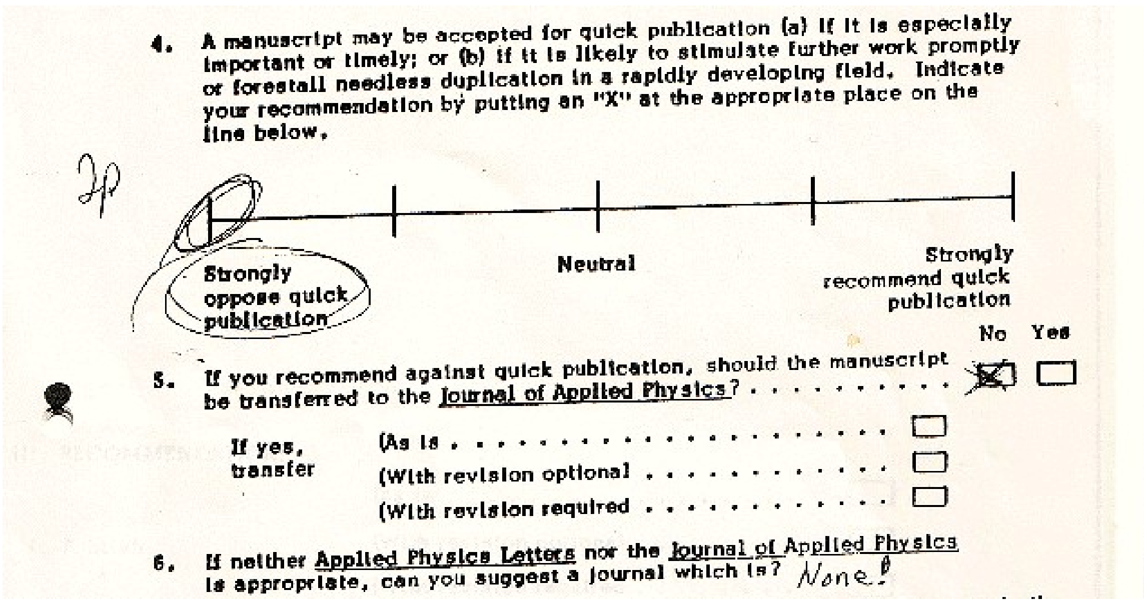


Figure 5. Schematics of the quantum confinement effect leading to the small crystallite sizes (“quantum wires”) in microcrystalline silicon obtained by electrochemical etching in HF (8).

Immediately after the successful experiments a manuscript was written by him and submitted in March 1990 to Applied Physics Letters. Volker Lehmann was not in favor of flowery lyrics in research and therefore his manuscripts were always very short, sometimes to the extend that they were much too short even for a letters journal. This manuscript was no exception and submitted with the title “Porous silicon formation: A quantum wire effect”, without any question mark at the end of the title. During the time the manuscript was reviewed he was already back at Siemens Corporation in Munich. Applied Physics Letters rejected the manuscript outright as shown in Fig. 6, to the utter disappointment of the authors.

The rejection was based on a long-winded review report basically stating that the authors were not capable of measuring properly and that the quantum confinement interpretation was ridiculous. The disappointment changed into disbelief and some anger when a Duke colleague, Prof. Hisham Massoud, pointed out a publication by L. Canham from a research center of the defense department in the UK, which had just appeared in Applied Physics Letters with the closely related title "Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers" (9), which had been submitted in May 1990, months after the rejected manuscript.



4. A manuscript may be accepted for quick publication (a) if it is especially important or timely; or (b) if it is likely to stimulate further work promptly or forestall needless duplication in a rapidly developing field. Indicate your recommendation by putting an "X" at the appropriate place on the line below.

Strongly oppose quick publication — Neutral — Strongly recommend quick publication

5. If you recommend against quick publication, should the manuscript be transferred to the Journal of Applied Physics? . . . . No [X] Yes [ ]

If yes, transfer (As is . . . . [ ]
(With revision optional . . . . [ ]
(With revision required . . . . [ ]

6. If neither Applied Physics Letters nor the Journal of Applied Physics is appropriate, can you suggest a journal which is? None!

a)

Porous silicon formation: A quantum wire effect

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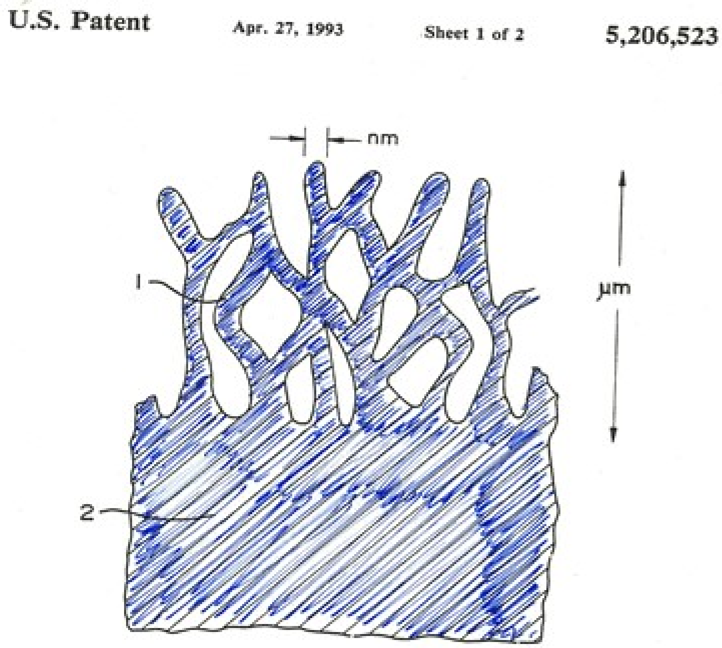
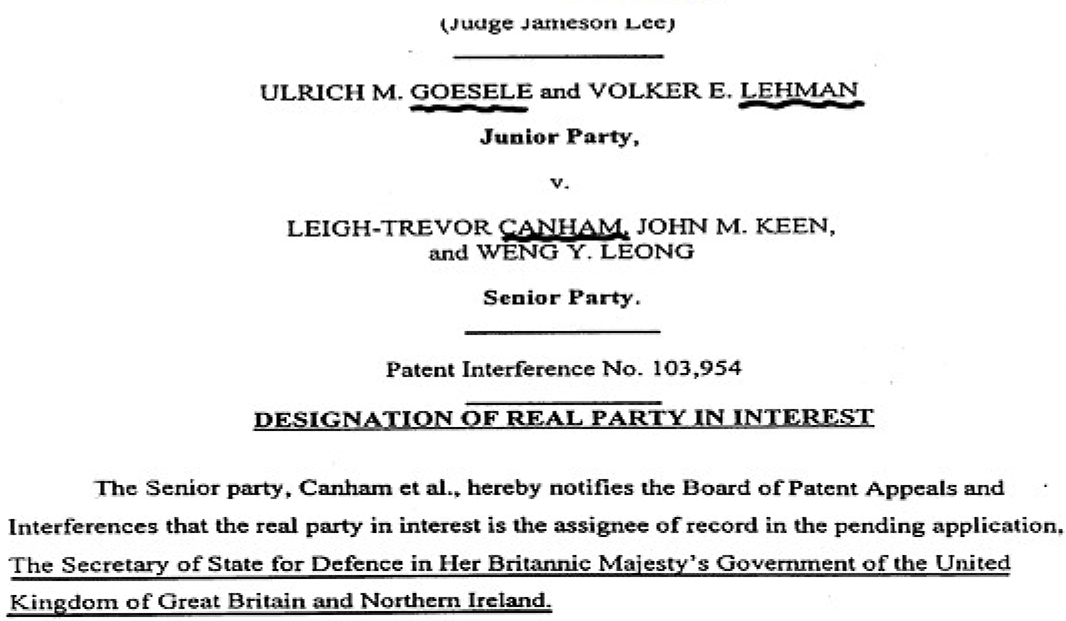
(Received 13 March 1990; accepted for publication 25 November 1990)

b)

Figure 6. a) First referee judgment on (2), shown for the benefit and encouragement of younger readers: never give up if you are sure about your work! b) The paper as it appeared in the first September 1991 issue of Applied Physics Letters, showing the submission date of March 1990.

After a lengthy appeal process, Applied Physics Letters finally accepted the manuscript in the original form (2), without any citation of the Canham paper (9) that was submitted later, and with the original submission date of March 1990. Unfortunately, the appeal procedure took so long that the paper was finally published only in September 1991 and has therefore naturally been considered as the second paper proposing quantum size effects for porous silicon after the 1990 Canham paper. Nevertheless, the paper has received more than thousand citations and firmly established Volker Lehmann as one of the influential researchers in the porous silicon community.





(Judge Jameson Lee)

ULRICH M. GOESELE and VOLKER E. LEHMAN

Junior Party,

v.

LEIGH-TREVOR CANHAM, JOHN M. KEEN,
and WENG Y. LEONG

Senior Party.

Patent Interference No. 103,954

DESIGNATION OF REAL PARTY IN INTEREST

The Senior party, Canham et al., hereby notifies the Board of Patent Appeals and Interferences that the real party in interest is the assignee of record in the pending application, The Secretary of State for Defence in Her Britannic Majesty's Government of the United Kingdom of Great Britain and Northern Ireland.

Figure 7. a) Schematics of the silicon "quantum sponge" as sketched in the above US Patent 5,206,523 which was later on given up in a patent interference procedure with the UK Ministry of Defence. b) Partial copy of legal interference document on porous silicon US Patent 5,206,523.
Shown for the benefit of younger readers: get out in time when science turns ugly, i.e. involves lawyers.

The quantum wire paper by Volker Lehmann (2) lead to a follow-up US patent in which for the first time a tandem cell silicon solar cell was suggested, based on a combination of bulk crystalline silicon and of microporous silicon with an appropriately higher bandgap. This concept of an all-silicon tandem cell making use of quantum confined silicon structures has just recently returned to active photovoltaics research, more than 15 years after the original suggestion. Already before the patent application was written, it became clear that the quantum wires were not at all straight as originally thought but formed an interconnected network (Fig. 7), which was then termed a "quantum sponge" in the US patent 5,206,523. Since Duke University was not interested in the patent it went personally to Volker Lehmann and U. G. It almost appears that Volker Lehmann divined the subsequent legal trouble - he got out of having to pay for getting the patent or any subsequent legal actions. Sure enough, the Ministry of Defense of the UK, a powerful entity (or more aptly put: enemy) that encompassed the research institution for which L. Canham worked, initiated a patent interference procedure (Fig. 7b). Suffice it to say that after a fairly unpleasant and lengthy period, in which the difference in the depth of the financial pocket of the UK Ministry of Defense and that of a Duke professor was the major consideration and decisive fact, the patent was given up in return for a check of $ 10.

Volker Lehmann always looked back at this patent issue more amused than really annoyed – it did not make any money in the end. It should finally be mentioned that during his time at Duke he was jogging regularly with U. G. and another faculty member, Prof. F. H. Cocks, who convinced Volker Lehmann at those numerous occasions that he should write a book on the electrochemistry of silicon. This would finally result in Lehmann's classic book "Electrochemistry of Silicon" (10), finished more than ten years later in Munich.

Back in Munich

When Volker Lehmann came back to Siemens he joined the research arm of the semiconductor branch where he remained to the end, even after Siemens begot Infineon, and Infineon quite recently begot Qimonda. It is remarkable and reflects his passionate interest for science and research that for all this time he managed to convince his management that work on the electrochemistry of silicon was important and should be funded.

Early on in his industrial career Volker Lehmann, married in the meantime father of two sons, decided that he would not go for the rat race necessary for a management position. He wanted to have sufficient time for his family and for his other passions. Besides art he enjoyed many types of physical activities – e.g. judo, skiing, and going by bike every morning from his home on one side of Munich to the other side of Munich where Siemens Central Research was located. Consequently, he took advantage of a program by Siemens Corporation, which allowed employees to reduce their working hours to a four-day week with an appropriately reduced salary. It was obvious that this would not shift him up the ladder of a management career, but it allowed him to do experiments himself, something he valued far more than having power over some co-workers in a managerial position. Back at Siemens he kept in touch with H. F., now a dean and Professor in Kiel, U. G., and many other researchers he had met and collaborated with, and kept producing major papers in the field of Si electrochemistry.

After U. G. also had returned to Germany as director of a Max Planck Institute in previous East Germany with the mission of doing basic research, Volker Lehmann joked that in his special position in an industrial lab, he had more freedom to do the research he was interested in than U. G. at the helm of a Max Planck Institute, not to mention a Dean (H. F.) founding a new faculty at the University of Kiel. He even claimed that while Siemens Corporation had been shifting emphasis from one area to another with time constants of typically 1 – 2 years, he had always managed to do his beloved porous silicon research independent of all changes by just changing the labels and the association with various areas of applications. He was also proud of having designed a working device for checking whether liquids contained dangerous HF or rather just water. These HF testers he fabricated at home and sold them privately, thus increasing the safety in many chemical labs.

During his time in Munich Volker Lehmann did first class research spanning the range from fundamental investigations (e.g. on the oxidation of light-emitting porous silicon (11) or the topic of current-voltage oscillations at the silicon electrode (12)) to revenue generating products like “bio-chips” in the time leading up to 2006. In particular he was the first researcher showing that a deep understanding of electrochemical etching of macropores (13) allowed to obtain a beautiful periodic array of such macropores in silicon that could be used as an almost perfect photonic crystal (14), which may also be structured to contain waveguides and other photonic structures (15). He also convinced U. G. to go back into the area of porous silicon again – this time in macroporous silicon for photonic crystals after the endeavor into quantum wires in microporous silicon had ended somewhat disappointingly, at least concerning the patent involved. This lead to a period of cooperation between Volker Lehmann, H. F., and U. G. in the area of silicon based photonic crystals (16). An example of such a structure is shown in Fig. 8.

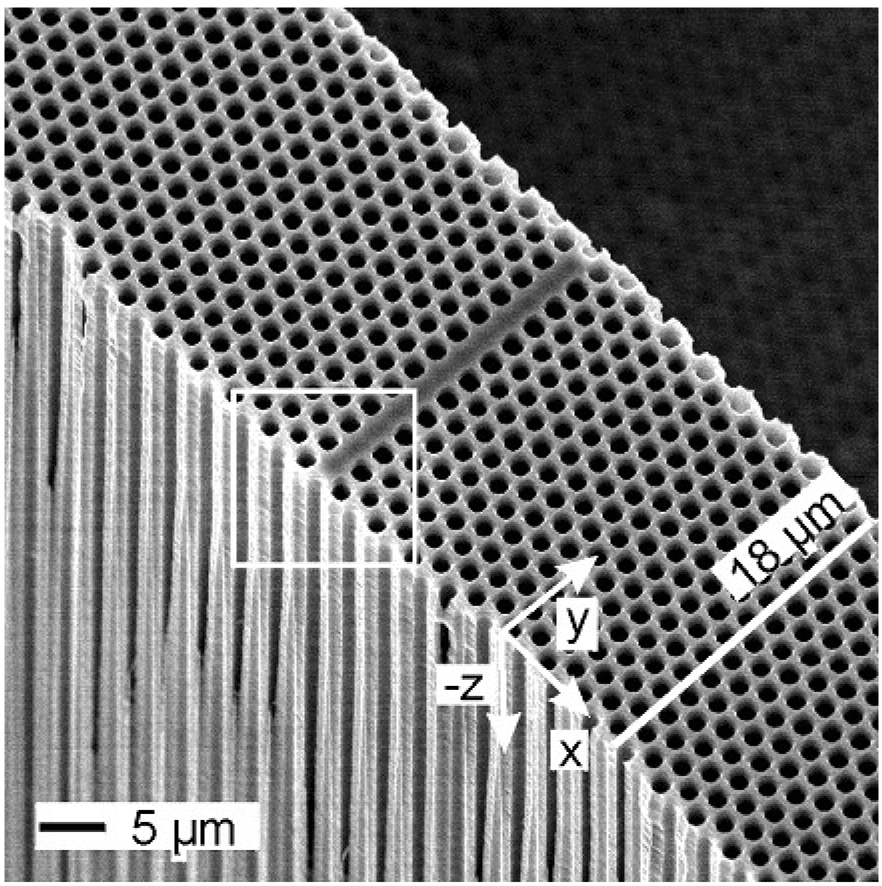


Figure 8. SEM picture of macroporous silicon ridge containing a waveguide the row with missing pores). Picture from (16).

Volker Lehmann tried hard to convince Siemens Corporation to use macroporous silicon as solid-state capacitor with superior properties (17). When management was not as excited as it should have been, concerning the prospects of such devices, he tried a somewhat unusual shock therapy. Together with another previous postdoc from the lab of U.

G. at Duke University, who also had ended up working for Siemens Corporation, he prepared a copy of a well-known trade journal containing a short and faked news article, in which it was reported that a Japanese competitor of Siemens Corporation had started to produce solid state capacitors based on macroporous silicon with thousands of wafer starts per week. At April fools day this copy was brought to the attention of management, and the whole chain of command up to the very top fell for it! Only good fortune and a remaining sense of humor within management prevented a bad outcome of this attempt to get the product accepted by management.

During his time at Siemens Corporation and after U. G. had returned back to Germany it became a yearly custom that Volker, the other postdoc mentioned above, and U. G. went skiing together for an extended weekend. It was an opportunity to see how fast and efficient Volker was - not only in doing his science but also in doing sports. He was of the opinion that ski lifts and cable cars were not for him and his friends, and that walking up the mountains would increase the pleasure in finally skiing down the slopes. In the evenings after a tough day on the mountains during dinner in a restaurant, he typically got out his lab book from the backpack he always carried along with him, and started to discuss open questions concerning pore formation mechanisms in silicon - conveniently ignoring the fact that no non-disclosure agreement had been signed.

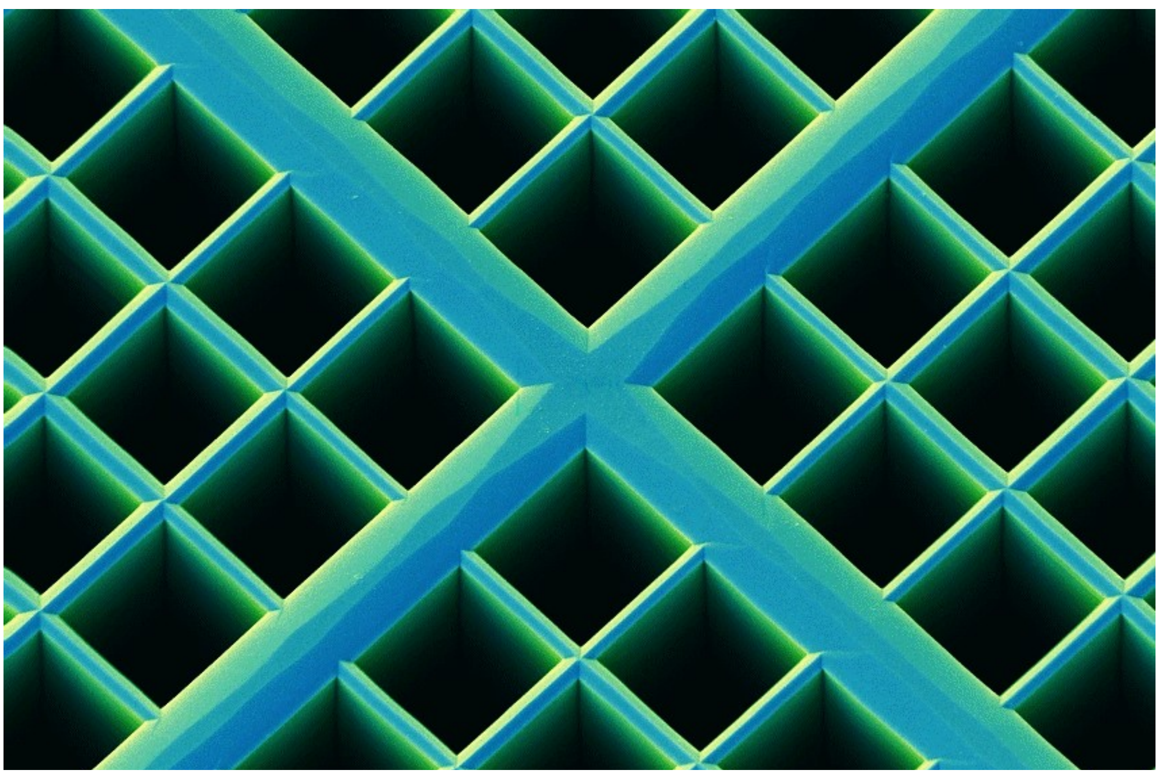


Figure 9. Macropores in Si after special KOH processing.

Similar things happened when the bi-annual “PSST” (Int. Conf. on Porous Semiconductor Science and Technology), a conference he never missed, took place in Tenerife in 2004. Hiking up the 12.000 feet tall volcano was a must (even so it was, theoretically, not allowed) with whoever went along. Porous rocks found along the way lead to discussions about porous semiconductors, and much progress in research and science resulted from these informal discussions during or after exertions.

His last contribution to science was an invited talk at the 2006 PSST; the picture in Fig. 9 is taken from this presentation. It illustrates once more two sides of a remarkable person: a scientist with unchallenged experience in porous silicon research and technology, and an artist who could find beauty wherever he looked.

Final Comments

Volker Lehmann was not only an outstanding scientist and accomplished artist, he was also a person with an extraordinary vitality, radiating good cheer and making friends easily. He was clearly enjoying life and consciously decided to do more research than management. He was always open and helpful and often the ringleader for extracurricular activities at workshops and conferences.

Volker Lehmann died unexpectedly and tragically on the 26th of May in 2006. He was married for 16 years and leaves a wife and two sons.

He has enriched the professional and private lives of many people. He will be missed and remembered. A picture showing him waiting for his friends to catch up with him is an appropriate ending to this article.

Figure 10. Volker Lehmann on one of his yearly skiing trips with one the authors (U. G.) being ahead of the crowd.

Acknowledgements

The authors acknowledge the hospitality of the Lehmann family over many years and discussions touching on the life of Volker Lehmann with various friends.

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