4. IBM T.J. Watson Research Center

4.1 TEM of Silicon - Silicide Interfaces

4.1.1 Some General Remarks

- For a self-respecting physicist, a post-doc trip to the USA was obligatory in the seventies. One year at the minimum, maybe two years pushing it.
  I stayed for almost 4 years. The reason went by the name of **Sara** for reasons given here. Nevertheless, after 2 years at Cornell University, I felt the urge to move on and accepted a post-doc position with **Paul Ho's** group a the **IBM T.J. Watson Lab** in Yorktown Heights.
  - I also had offers from **Bell Labs**, and Cornell University and had to make a tough choice. Well, Yorktown Heights was not so far (by train) from New York City where Sara lived, and that was a factor in the decision making process. As it turned out, it was a good decision. I was able to do a lot of good research, including some "on-the-side" stuff that turned out, quite unexpectedly, to dominate most of my later work. Just as unexpected was that Paul Ho's group turned out to be a kind of breeding ground for future German university professors. Besides me, we have Ulrich Gösele, Fanz Faupel, and Ludwig Schulz.
- The T.J. Watson Research Center of IBM really pampered its scientists. You could work there every hour of the week, including Sunday nights, and you even had access to the library and other resources all the time. The otherwise strict IBM dress and behavior code did not apply either.
  However, a strange and slightly scary thing was the yearly "evaluation", based on the superstition of the management that you could somehow measure the performance of your tame scientists. Us young guys worried a bit until an older and experienced colleague took us aside and said: “Don’t worry. We are by definition much smarter than the guys from personnel management. As soon as we know what they want, we know what to do”. And right he was. If you worked, for example, on the topic of silicides (then considered to be important for the next generations of Si microchips), you teamed up with your colleagues from Bell Labs and maybe a few other organizations, until you reached critical mass for running your own conferences with conference proceedings and many invited contributions, awarding prizes to each other and so on. Quite obviously you were doing important and successful work. It took many years before the management caught on.
  - That was fun but it didn't stop there. Evaluating scientists became fashionable and scientists knew what to do. Keep you publications profile optimized. Publish whatever you have as many times as you can get away with it, and if you don’t have results, see if you can “borrow” the stuff of somebody else. Happened to me and to many others.
  - Of course, we scientist also have that superior recipe for furthering one's career: just did good work. When I look back at my first progress report, I’m amazed at how busy I was. That’s why I present it here:.

Progress Report 1979

- The progress report contains 6 topics. The last one is “Si – Silicide interface in cross-section”. It was the major part of my work at IBM and therefore will be dealt with first.

4.1.2 Silicon - Silicide Interfaces

- I I was supposed to study silicon - silicde interfaces and to produce very thin polycrystalline Si (using the technique I knew from my collaboration with Siemens). That's what I did, using not only the (mediocre) TEM of IBM but also the top TEM at Cornell for HRTEM studies. That instrument was only a 6 hour drive away, counting as next to nothing in the good old US of A.
  - Silicides, i.e. metal-Si compounds, were deemed important for the future of microelectronics at the end of the 1970ties. You could either sputter them on or form them by a solid state reactions with the Si. The idea was to study their formation by coating silicon with some metal followed by some annealing. A silicide forming reaction could occur because the metal diffuse into the Si, eventual forming the most Si-rich silicide found in the phase diagram, or Si diffusing into the metal producing the metal - rich silicide. Continuing heating (and possibly increasing

the temperature) would produce all the other silicides the phase diagram provided, i.e. Ni_2Si, NiSi and $NiSi_2$. But things often were different from this simple view of silicide formation. That much was known but there was still lots of room for a detailed investigation. I looked at the Pd-Si, Pt-Si and Ni-Si system. I took the very first HRTEM picture of a heterogeneous interface and a lot of other spectacular micrographs, providing a lot of new insights.

This might be the right place to explain something not obvious to today microscopists: Cross-sectional TEM and high resolution TEM were almost unknown in 1977 when I first used it in Cornell. When I applied the technique to the silicide research at IBM, I was rather experienced but also a member of a very small peer group. The introduction to the "lost book" paper gives an idea of this situation.

4.1.3 Publications

Major Publications

Not counting conference proceedings and other small stuff, the total count considering my published silicide studies is three (No. 25, 42, and 43 on the list) . Just fine but some small stuff I did on the side produced many (small) publications since some colleagues who had already fully understood what smart scientists must do to get ahead, took my pictures and interpreted them in many fascinating ways I wouldn't have dreamed of. More to that later.
Well - here they are

25 **FÖLL, H., HO, P., TU, K.N.: Cross-sectional TEM of silicon-silicide interfaces. J. Appl. Phys. 52 (1981) 25**
(146 citations)
A good example for the deterioration of pictures. The link leads to a high-quality scan made from the original journal. The whole thing is quite yellow and faded and some of the pictures (in particularly Figs. 7 - 9 show nothing at all any more. Figs. 2, 4, and 8, by the way, are the very first high resolution TEM pictures showing heterogeneous interfaces.

42 **FÖLL, H., HO, P.S., TU, K.N.: Transmission electron microscopy of the formation of nickel silicides.** Phil. Mag. A 45 (1982) 31
(167 citations)
Much better paper and picture quality

43 **FÖLL, H., HO, P.S.: Transmission electron microscopy investigation of silicide formation on slightly oxidized silicon substrates. J. Appl. Phys. 52 (1981) 5510**
(47 citations)

I do have the three *published* silicide articles above to my name plus a number of others to be discussed later. On top of that, there is also a major unpublished article. I call it the *"lost book" article*. It was completely finished but all I have now is an almost finished draft - without reference list, some details like numbers, and the symbols not provided for by normal type writers. It is actually contained as number 50 in my list of publications. Here it will be No. i on my list of imaginary publications :

¡ **Föll, H. and Kuan, T.S.: SStructural properties of silicide/Si interfaces: Transmission electron microscopy**
in: Metal/Si and Silicide/Si interfaces, eds. P.S. Ho and G.J. Rubloff (Elsevier), in press, invited paper (contribution finished, but book never published)
Part 1
Part 2

We were asked to write this article for a book our elders (but not necessarily betters) planned to issue. Being young and given to scientific idealism, we actually did as asked. Some of our elders (and definitely not betters), including the potential editors, did not. The book thus was never published.

I include it here because it gives a detailed account on what TEM meant at the end of the 70ties. It also included - for the first time, I believe - the notion that interface dislocations contain steps by necessity and that this introduced new conditions on possible geometries.
I also include it because it gives me the opportunity to present a few more pictures. In this case explanations are given in the Fig. captions

Minor Publications

My TEM pictures of Si - silicide interfaces spawned a number of minor publications and conference proceedings. “Minor” is in the eye of the beholder, some papers were quite well received (see below). However, they were minor to me since mostly I didn’t write them. I had already left IBM when these papers were written.
Here is a list with some remarks: The numbers refer to the numbers given in the publication list. There are no new pictures in these papers

36 **EIZENBERG, M., TU, K.N., FÖLL, H.**: Formation of shallow silicide contacts to Si using Pt-Si and Pd-Si alloy films. J. Appl. Phys. 52 (1981) 861 (53 citations)
A respectable paper in a good journal with a good number of citations. It also contains two TEM pictures not prepresented here before

37 **EIZENBERG, M., FÖLL, H., TU, K.N.**: Shallow silicide contacts formed by using co-deposited Pt_2Si and $Pt_{1,2}Si$. Appl. Phys. Lett. 37 (1980) 547(23 citations)
Just a letter but in a good journal. Contains 1 TEM picture used here before.

40 **FÖLL, H.**: Lattice imaging of silicide-silicon interfaces. Jap. J. Appl. Phys. Oyo Buturi (50th Anniversary Issue) 51 (1982) 221; invited paper in jap. language (28 citations)
My one and only paper published in Japanese. I was invited for a contribution and some poor soul had to translate my prose.
Contains no new pictures and is, in parts, inspired by publ. No. 41 below

41 **FÖLL, H.**: Lattice imaging of silicides-silicon interfaces. Phy. Stat. Sol. (a) 69 (1982) 779 (28 citations)
I felt very good about this paper, considering t a minor break-through for interprerting HRTEM pictures of interfaces. The number of citations, however, is disappointing .
No new TEM pictures but some drawings that appear at the end of the "lost book" (see above).

44 **HO, P.S., SCHMIDT, P.E., FÖLL, H.**: Stoichiometric and structural origin of electronic states at the Pd2Si-Si interface. Phys. Rev. Lett. 46 (1981) 782 (88 citations)
A Phys. Rev. Letter, no less! Considered very prestigious.
No new pictures.

45 **SCHMIDT, P.E., HO, P.S., FÖLL, H., RUBLOFF, G.W.**: Electronic states and atomic structure at the Pd_2Si-Si interface. J. Vac. Sci and Tech. (55 citations)

51 **TU, K.N., OTTAVIANI, G., GÖSELE, U., FÖLL, H.**: Intermetallic compound formation in thin-film and in bulk samples of the Ni-Si binary system. J. Appl. Phys. 54 (1983) 758 (128 citations)
One of "my" more successful papers! I contributed Fig. 2. Fig. 2a is "new" and shown here.

53 **SCHMIDT, P.E., HO, P.S., FÖLL, H., TAN, T.Y.**: Effects of variations of silicide characteristics on the Schottky-Barrier height of silicide-silicon interfaces. Phys. Rev. B. 28 (1983) 4593 (44 citations)

4.1.4 Pictures

Pictures in the "Philosophical Magazine" are still quite good and of decent size; the paper has only yellowed a bit. The Journal of Applied Physics, highly prestigious then, has badly aged and not much can be recognized on the pictures.

- In what follows I present the originals as far as still at hand and some auxiliary pictures.

Si - Silicide Interface pictures

Part 1 **Pictures t publ. 1**

Part 2 **Pictures t publ. 2**

Part 3 **Pictures t publ. 3**

Part 4 **Pictures minor publ. and auxiliary**

- Next, some pictures intended to be part of the "lost book" mentioned above

Pictures to "lost book"