Neuron-Silicon Junction or Brain-Computer Junction?
Peter Fromherz

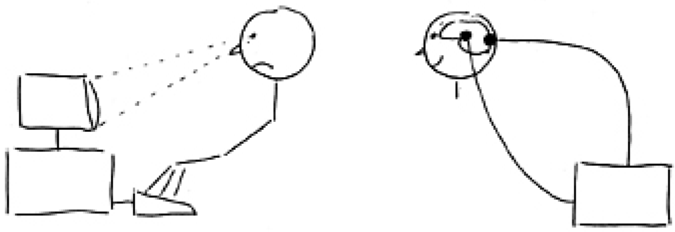

Fig. 1 Brain-Computer Junction
[a] Classical mechano-optical pathway eye-screen and finger-keyboard.
[b] Imaginary ionic-electrical junction of the computer with the optical and motor centers of the cerebral cortex. [Fromherz, 1985]

I first observed nerve cells and silicon wafers while working on two distinctly different degree dissertations in my laboratory at the University of Ulm in 1984. At the time, we were studying how the electrical activity of nerve cells influenced fluorescent dyes and the effects of artificial membrane layers on microscopic silicon electrodes. Enthused by the results, I used the occasion of the 20th Winter Seminar "Molecules, Information and Memory" presented by Manfred Eigen in January 1985 to present a paper entitled *Brain on Line*? The Feasibility of a Neuron-Silicon Junction, in which I outlined how a direct electrical contact between a nerve cell and silicon (and vice versa) could be constructed. In the paper, I wrote: "The information processing of the networks of neurons in a brain and of the networks of silicon chips in a computer is coupled at the present moment macroscopically through the opto-mechanical pathway eye-screen and finger-keyboard (Fig. 1a). Is a direct microscopical coupling feasible (Fig. 1b)? The utopian question may be shaped into a proper scientific problem: How to design a neuron-silicon junction?"

The matter did not remain at the design stage. However, a prerequisite for carrying out a neuron-silicon junction was the process of learning and mastering the production of silicon chips and the cultivation of nerve cells — by a small team working in one and the same laboratory. Six years later, we published a description of the first direct electrical junction of a nerve cell to a silicon transistor[1]; 10 years later, the first direct electrical junction of a silicon microstructure to a nerve cell[2].

Since then, we have performed a detailed study of the physics of the coupling of neurons and silicon[3-6]. We understand how the quality of the signal transmission is effected by the geometry of the cell-chip contact and by the electrical properties of the cell membrane and of silicon.

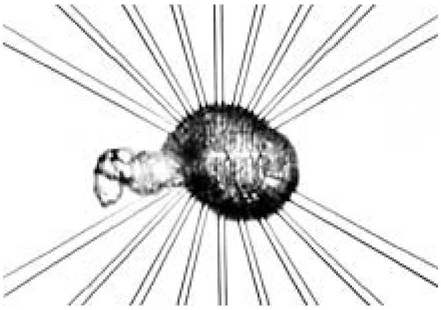

Fig. 2 Neuron-Silicon Junction. Nerve cell [approximately 60 micrometers in diameter] of a leech ganglion in direct contact with 16 transistors in silicon. Electrical voltage impulses in the cell directly effect the chip's electronics[4]

All of these studies were carried out using large nerve cells (approximately 60 micrometers in diameter) of leech ganglia. As an example, Fig. 2 illustrates the "wiring up" of such a nerve cell with the 16 transistors of a silicon chip. The first junctions with nerve cells from the brain of a rat have recently been successfully performed[7]. Here, the small size of these cells (about 10 micrometers) poses particular problems.

These lengthy and difficult experiments have shown us just how large a gap really exists between test-tube experiments involving a neuron-silicon junction and the interfacing of the brain and the computer. We must keep in mind that we are dealing with two completely different aspects here — a physical one and an informational one.

To begin with: the physics of the direct junction of nerve cells and silicon is based on the contact of the neurons' thin (5 nanometer) cell membrane with the thin (20 nanometer) layer of quartz which makes up the silicon's water-tight casing. Only when the contact is extremely close (about 30 nanometers) does an electrical coupling take place through the electrical field (electrostatic induction). This tight junction can be successfully created in the test-tube with clean silicon chips and nerve cells which have been dissected from tissue samples. The form which such a contact would take in the tissue of a nerve fiber or of the brain cannot be foreseen at the moment. After all, this is not merely a matter of maintaining a few random contacts; if the brain and the computer — two separate worlds miniaturized down to microscopic level — are really to be brought into connection with one another, and if an adequate level of communication is to come about as a result, then millions of contacts must be set up.

Moreover: it is not sufficient to install contacts between the brain and the computer which exchange some sort of informational bits in both directions. Both the brain and the computer must directly understand the semantics of a foreign language without the abstraction and adaptation accomplished by means of keyboard and monitor. Both operating systems have to communicate directly with each other in a meaningful way. As long as we do not know how the brain functions — what relationship exists between its microscopic electrical signals and its macroscopic semantics — an informational interface remains impossible even if the physical junction were feasible.

What can be done? Physicists will carry on with the effort to establish thousands of contact points between nerve cells and silicon microstructures. Experiments to achieve this — in cooperation with major firms in the microelectronics industry — are now underway. Even if this can only be done in a test-tube, it will provide scientists with a basis for understanding how larger hybrid networks composed of neuronal and technological elements communicate with each other on the level of semantic information. Thus, we might learn something about the function of the brain.

Setting up contacts within living tissue is another problem. One solution might be an ingenious form of coating of the chip or the cell. Here as well, it will be necessary to first carry out basic research on the biology, chemistry and physics of cell adhesion.

The process of achieving a direct junction of individual nerve cells and individual silicon microstructures has opened our eyes to the difficulty of establishing a linkage between the brain and the computer without the mediation of the opto-mechanical pathway eye-screen and finger-keyboard. The apparent problems posed by this junction on the physical and informational levels are so enormous that it is impossible today to predict whether such a form of communication will ever become a reality. For this reason, an ethical consideration of issues such as "chip in the brain" or "brain in the computer" would be unfounded and superfluous.

Notes:

1. P. Fromherz, A.Offenhäusser, T.Vetter, J.Weis, A Neuron-Silicon Junction: A Retzius-Cell of the Leech on an Insulated-Gate Field-Effect Transistor, in: **Science** 252 (1991) 1290-1293.

2. P. Fromherz, A.Stett, Silicon-Neuron Junction: Capacitive Stimulation of an Individual Neuron on a Silicon Chip, in: **Physical Review Letters** 75 (1995) 1670-1673.

3. P. Fromherz, C.O.Müller, R.Weis, Neuron-Transistor: Electrical Transfer Function measured by Patch-Clamp Technique, in: **Physical Review Letters** 71 (1993) 4079-4082.

4. R.Weis, B.Müller, P.Fromherz, Neuron-Adhesion on a Silicon Chip probed by an Array of Field-Effect Transistors, in: **Physical Review Letters** 76 (1996) 327-330.

5. R. Weis, P.Fromherz, Frequency Dependent Signal-Transfer in Neuron-Transistors, in: **Physical Review** E 55 (1997) 877-889.

6. A. Stett, B.Müller, P.Fromherz, Two-Way Silicon-Neuron Interface by Electrical Inductance. in: **Physical Review** E 55 (1997) 1779-1782.

7. S. Vassanelli, P.Fromherz, Neurons from Rat Brain coupled to Transistors, in: **Applied Physics** A (1997) in press.