Smallest Nanoelectronics with Atomic Devices with Precise Structures

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(I expect all the readers to read the sidebar at first, where all the concepts in this article are presented at page 8. I appreciate it if this article is typeset like that.)

Since its invention in 1948, the transistor has revolutionized our everyday life - transistor radios and TV's appeared in the early 1960s, personal computers came into widespread use in the mid-1980s, and cellular phones, laptops, and palm-sized organizers dominated the 1990s. The electronics revolution is based upon transistor miniaturization; smaller transistors are faster, and denser circuitry has more functionality. Transistors in current generation chips are 0.25 μm(micron) or 250 nanometers in size, and the electronics industry has completed development of 0.18 μm transistors which will enter production within the next few years. Industry researchers are now working to reduce transistor size down to 0.13 μm - a thousandth of the width of a human hair. However, studies indicate that the miniaturization of silicon transistors will soon reach its limit.

For further progress in microelectronics, scientists have turned to nanotechnology to advance the science. Rather than continuing to miniaturize transistors to a point where they become unreliable, nanotechnology offers the new approach of building devices on the atomic scale [see sidebar]. One vision for the next generation of miniature electronics is atomic chain electronics, where devices are composed of atoms aligned on top of a substrate surface in a regular pattern. The Atomic Chain Electronics Project (ACEP) - part of the Semiconductor Device Modeling and Nanotechnology group, Integrated Product Team at the NAS Facility has been developing theory for understanding atomic chain devices, and the author's patent for atomic chain electronics is now pending.

A critical element in transistor functioning is the use of dopants. Dopants are impurities added to silicon to manipulate and control electronic properties of the material. Typically, there are several thousand dopant atoms in a transistor and these appear as a dopant "jelly" as in Fig. 1(a). With these large numbers of dopant atoms, the precise location of the atoms in the transistor is not very important to transistor functioning. However, when the transistor size is reduced to less than 0.1 μm as in Fig. 1(b), the number of dopant atoms is small, less than 100 - each dopant position then matters. Current manufacturing technology cannot control the location of the few dopant atoms precisely and this will cause small variations in transistor functioning. This is fatal when millions or billions of transistors are integrated in a computer chip, since these slight variations can cascade from one device to the next and eventually malfunction. A solution to this miniaturization problem has been devised by ACEP, which is to create all the device structures with atomic chains laid out in a regular precise pattern by anchoring atoms to a substrate as in Fig. 1(c)

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A second critical element in transistor functioning is that the output of the transistor should be a magnification of its input - this is called *gain*. To create atomic chain transistors that produce gain, ACEP research has found that the means is to use the so-called *field effect* (see sidebar).
To build a field-effect transistor at the atomic scale (as at large scales), we need to devise chains with semiconductor and metal properties. First, ACEP team tackled a simple problem theoretically: If we can arrange silicon atoms along a line floating in air, is this chain semiconducting? The answer is surprising: although bulk or thin film silicon is semiconducting, the silicon chains

are always metallic. Fortunately, ACEP research found that a magnesium chain is semiconducting, even though ironically, bulk magnesium is metallic.

Substrate determines chain properties

Of course, we cannot float atoms in air, but need to place them on top of a substrate. Surface atoms of the substrate attract atoms in the chain and hold them at fixed positions. The substrate has atomic scale corrugations on the surface and these may be used to create a precise pattern as in Fig. 2(a). However, ACEP members have found that this force is too weak to secure atoms reliably (Fig. 2(b)). ACEP members concluded that a chemical bonding scheme to secure atoms to the substrate as in Fig. 2(c) was the reliable approach to follow. Research soon showed that the chain properties are strongly influenced by the substrate material and surface orientation, when chemical bonding is relied upon. In fact, the same atomic chain can be either metallic or semiconducting depending on the details of the substrate. For example, silicon chains with two chemical bonds to the substrate atoms are semiconducting. Otherwise silicon chains are metallic. Aluminium chains with one chemical bond are semiconducting. Otherwise, aluminium chains are metallic.

A further concern was that electrons travelling along the atomic chain may detour into the substrate through chemical bonds and possibly exit through a neighboring chain, resulting in the short-circuit of two atomic chains. This short circuit is fatal for electronic applications and must be avoided. We have clarified the conditions on which the substrate surface provides an insulating surface in the chemical bonding scheme. According to this, silicon and germanium crystals offer good insulating substrates.

Putting it all together

So far, ACEP team have achieved the first step towards the development of atomic chain electronic devices. On top of a silicon substrate, we can attach germanium atoms with two chemical bonds as shown in Fig. 3. This structure is a semiconducting chain on an insulating substrate. Nearby chemical bonds on the substrate are saturated with hydrogen atoms so that they are electronically inactive. We now have a component for a field effect transistor on the atomic scale.

Collaborations

In this type of research, collaboration with the experimentalists is essential for success. ACEP members are collaborating with Dr. Dongmin Chen of the Nanophysics Group, Boston's Rowland Institute, who characterizes electronic properties of atomic structures with STM in connection to atomic devices. ACEP members are also collaborating with Prof. Richard A. Kiehl in the Electrical Engineering Department, University of Minnesota, who studies an autoformation of atomic structures that may lead to a breakthrough for mass production of atomic-scale devices.

Acknowledgement:

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Bio:

Toshishige Yamada is a Senior Research Scientist with CSC at NASA Ames Research Center. He obtained a Ph.D. in Electrical Engineering from Arizona State University under Prof. D. K. Ferry. He held positions at NEC Corp. Microelectronics Research Labs., Kawasaki, Japan, and Stanford

University. NASA Headquarters filed a patent application on his research in atomic chain electronics last year on this innovation, and the work was presented in an invited talk in the 196th Electrochemical Society Meeting last fall.

SIDEBAR ONE

Transistors: electronic workhorses

At the heart of today's electronics world are millions of tiny transistors. Their main function is to amplify a small input signal into a large output signal as shown in Fig. A1(a). The most popular transistor in the present electronics is a field-effect transistor (FET). To understand the operation of an FET, we can find an analogy to a flexible hose system with weight on it. When the weight is small, water flow is not hindered as shown in Fig. A1(b). As the weight is increased, the hose becomes pinched, resulting in less water flow. In this analogy, the weight corresponds to the input signal and the water passing through the hose is the output.

In a field-effect transistor, the input is a voltage applied to the gate electrode, and the output is a current flowing between the source and the drain. When the gate voltage is low, electrons flow freely from the source to the drain. When the gate voltage is high, electrons are repelled under the gate and fewer electrons flow. This is the so-called field effect.

In our analogy of water flow in a hose, the constriction caused by the weight depends on the material of the hose. For example if the hose is a steel pipe, then the weight (input) has little effect on flow (output). In the same way, if the substrate of an FET is a metal, the gate voltage has little effect on current flow. Therefore, we need a material corresponding to a flexible hose - a semiconductor.

What FET property corresponds to the flexibility of the hose? That is doping, or intentional inclusion of impurity atoms in the semiconductor substrate. In fact, by manipulating doping, we can change a semiconductor from something very close to an insulator to something very close to a metal.

Figure caption:

Fig. 1: The evolution of transistor miniaturization has taken electronic devices from the macroscopic scale (a), > 1 μm (micron). Ten thousand dopant atoms form a jelly area (smooth distribution), and determine the switch-on voltage. Transistors miniaturized down to the mesoscopic scale (b), 0.1 to 0.01 μm, have different switch-on voltages depending upon precisely where the dopant atoms are located. To solve this problem, researchers at NAS Facility have patented an atomic device concept using atomic chains (c) < 1 nm long rather than further miniaturization of conventional transistors.

Fig. 2: (a) Atomically precise structure using the substrate atomic lattice as a template. Two confinement schemes for adatoms on top of the substrate: (b) floating scheme and (c) chemical bonding scheme. Green dots are hydrogen atoms for surface bond passivation.

Fig. 3: Example of insulated semiconducting chain of germanium atoms on top of a silicon (100) substrate, where unused regions are hydroginated.

Fig. A1: Principle of FET: (a) amplification; (b) transistor operation and water hose analogy.

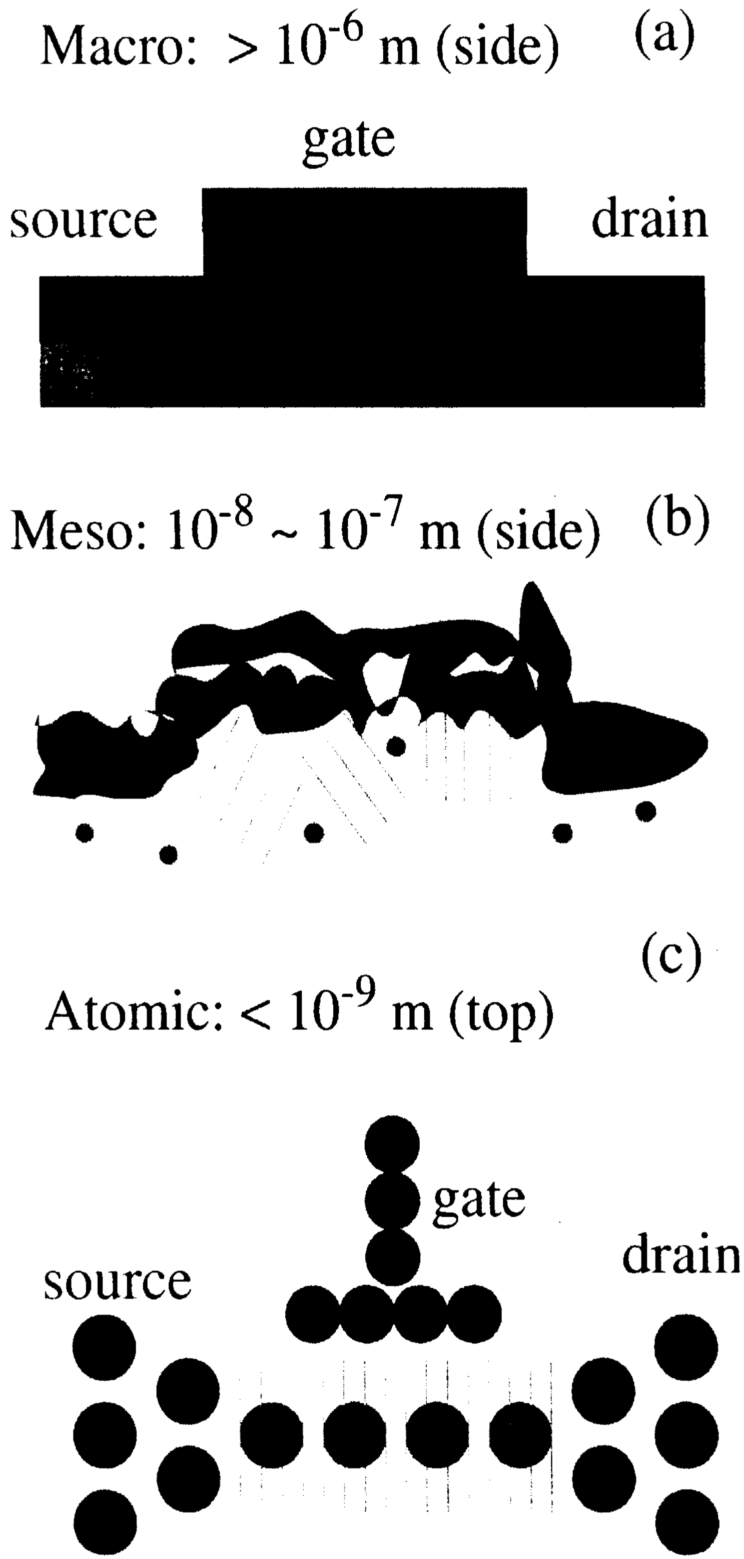

Macro: > 10-6 m (side)
(a)
gate
source
drain
Meso: 10-8 ~ 10-7 m (side)
(b)
(c)
Atomic: < 10-9 m (top)
gate
source
drain

Fig. 1

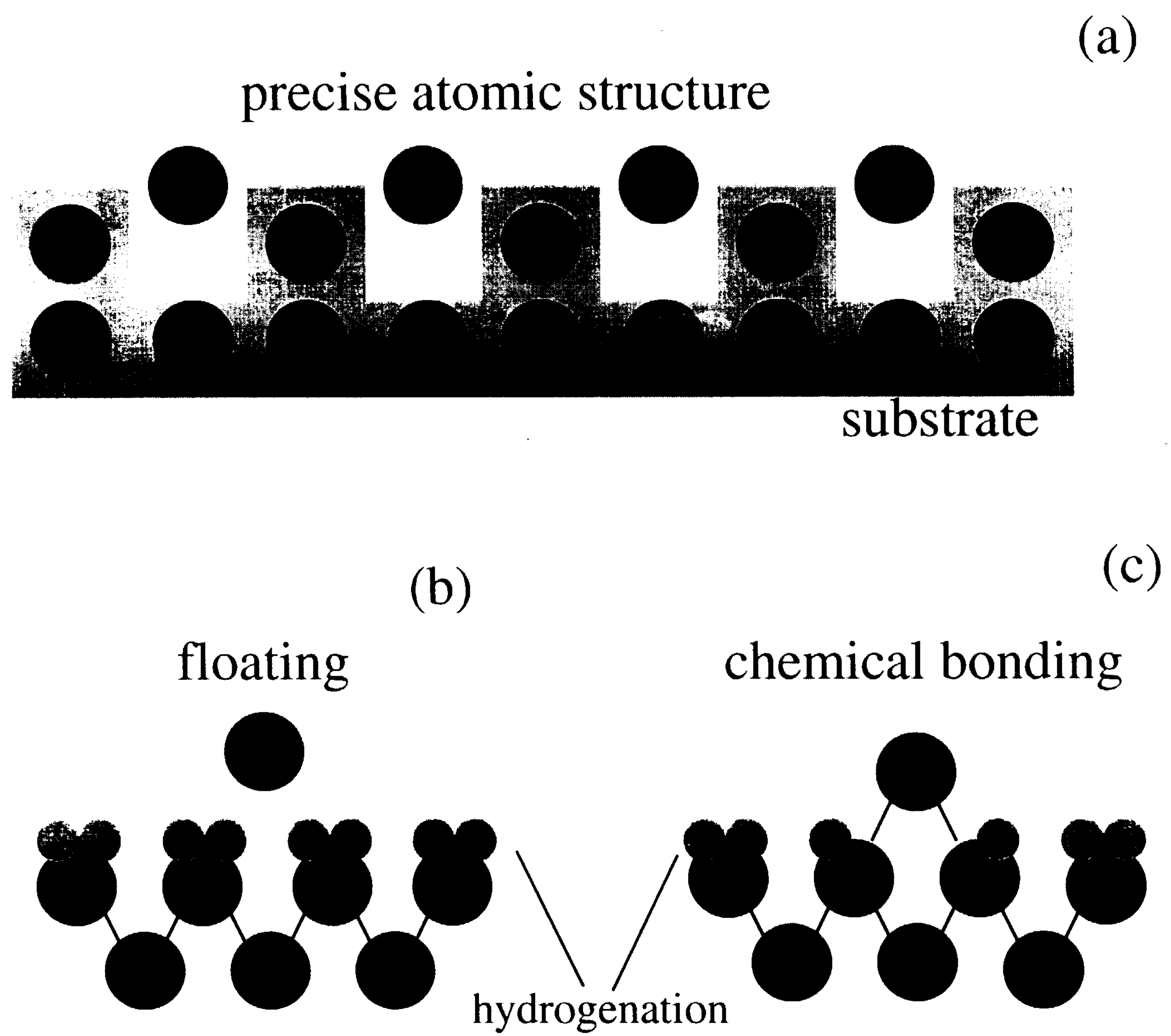

(a)
precise atomic structure
substrate
(b)
floating
(c)
chemical bonding
hydrogenation

Fig. 2

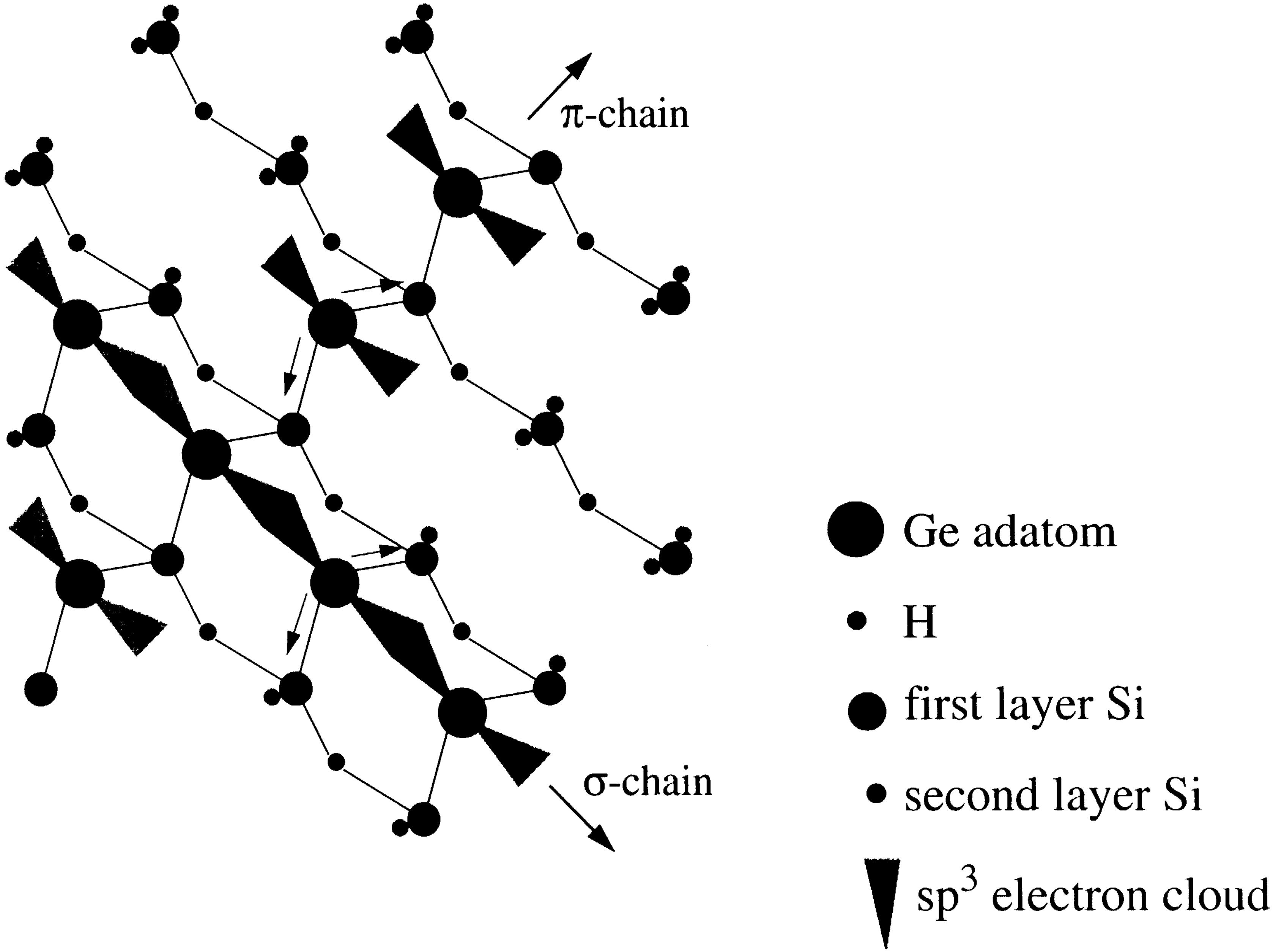
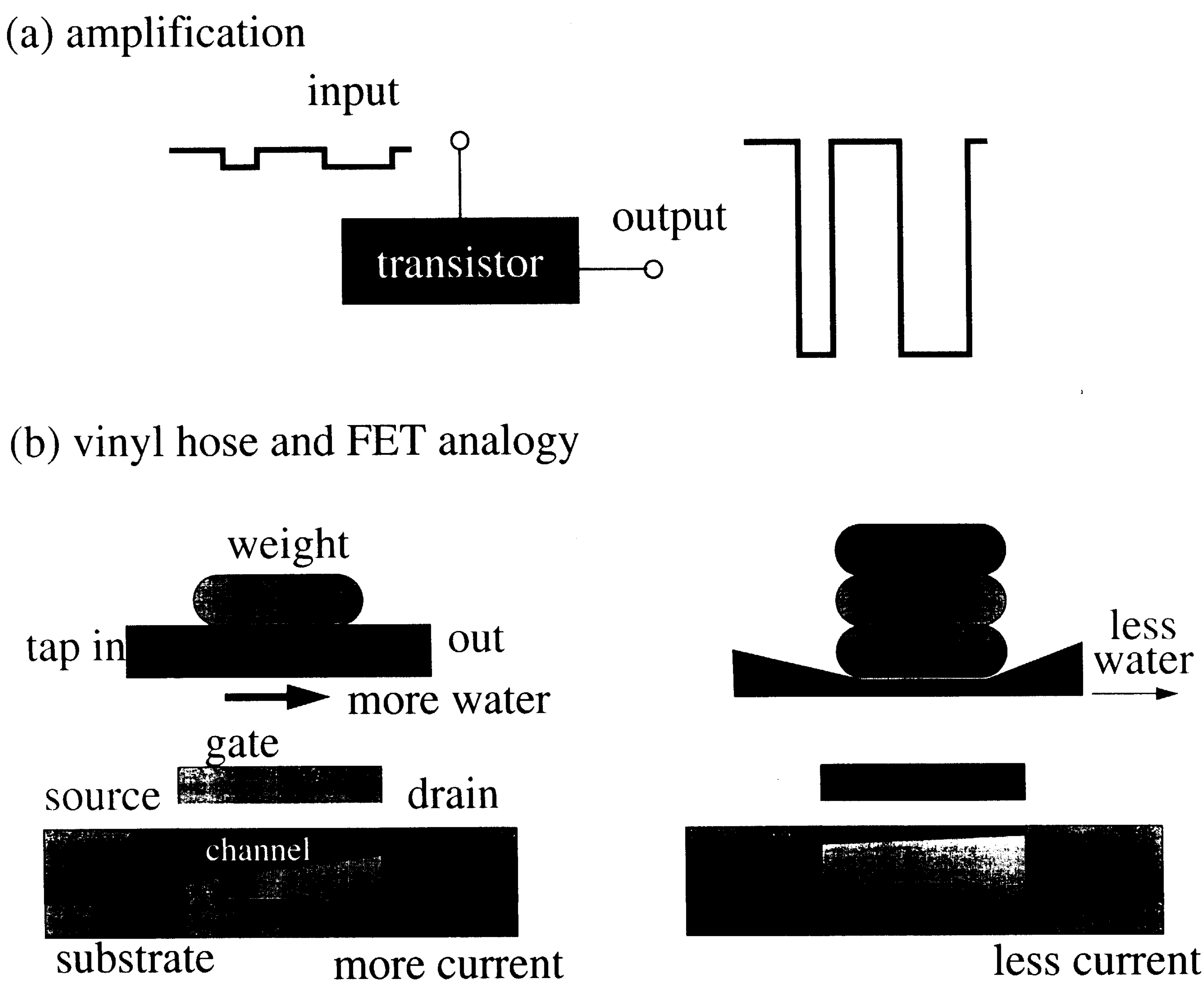

π-chain
σ-chain
Ge adatom
H
first layer Si
second layer Si
sp3 electron cloud

Fig. 3



(a) amplification
input
transistor
output
(b) vinyl hose and FET analogy
weight
tap in
out
more water
gate
source
drain
channel
substrate
more current
less
water
less current

Fig. A1