SPACE ENVIRONMENT — A NEW DIMENSION IN THE PREPARATION OF UNIQUE SOLIDS

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This report is about solids; primarily electronic solids, and what the absence of gravity in space can do in achieving homogeneity in materials that we can not achieve on earth. First, though, some remarks will be made regarding materials, in general, and solids, in particular.

Up to about 15 years ago, the materials were primarily a matter of art, of trial and error. Science was lagging behind. However, things have changed. Now, theoretical or scientific or fundamental predictions about devices, structures, and components are way ahead of materials technology. We speculate, in fact, we show, on sound basis, what we could do if materials were available; and during the last 10 or 15 years, nearly all of our expectations were realized, when the right materials were available. This is true even in the case of high-strength materials, the laser, semiconductor devices, and many of the other solid-state electronics.

The three parameters that worry us the most about materials are: first, structure — that is, how perfect the materials are in terms of having their atoms in the right places; two, purity — how pure they are; and, three, how homogeneous they are. In other words, what are the variations in purity and structural defects from one point of the material to the other? Two of these problems have come a long way in the last 15 years. Regarding structure, we can now prepare materials that are structurally perfect. Particularly in the electronic area, we can prepare silicon crystals and others which have absolutely no structural defects; all the atoms are where they should be. Regarding purity, we have achieved the purest materials as we know how to detect and identify. The purity in some of the electronic materials is in parts per trillion or better. However, we do not use very pure materials, for they are not good for very much. They must have impurities in them, but those impurities must be very carefully controlled and be extremely homogeneously distributed. Here is the stumbling block: how do I identify this type of heterogeneity? As we have been making progress in identifying them, we have been detecting more and more heterogeneities, which we can directly trace to gravity and which we can do nothing about on earth.

To be specific, you heard earlier that if one, on earth, is about to prepare a solid, he must use a liquid. One must first melt the solid for a solution by heating it. There is no way that one can avoid the heat convection which forms gradients — changes in temperatures. The heavier things tend to settle in the liquids or fluids, and the lighter things tend to rise. Why is that harmful? When these convections take place, the temperature changes at the places where you need perfect control, that is, between the solid and the melt. This means that the rate at which the solid is formed changes, and once that happens, there is absolutely nothing that you can do to make sure that that solid is going to be homogeneous. Why is that important? It is important on a microscale, for example, in the case of the ordinary casting of metals, of superalloys, which we need for high-temperature/high-strength applications, as in the case of jet engines and the like. There is a serious problem that has to do with gravity. As you cast a metal, the bottom part of the metal or the container is going to cool; so it solidifies, but in between that solid and the melt above it, there is an intermediate region where you have both solid and melt. As the solid solidifies, in many instances some of the lighter elements of that liquid are not incorporated into the solid, but are left behind in the melt. The melt becomes lighter directly above the solid and shoots up in jetlike form through the intermediate stage which is a mix of solid and liquid. This mixture then thins out and destroys the solid configuration and creates what people now call freckles or channels. These defects are very detrimental to the strength and other characteristics of materials.

Microscopic convection becomes of paramount importance in the electronic materials, the semiconductors. These devices are becoming smaller and smaller by the year. In the so-called integrated circuit, we assemble hundreds of devices the size of the order of microns. You can barely see them with the naked eye. This implies that on a wafer — a piece of silicon 0.75 in. diam by 1 in., there are about 1 million devices. You have to make sure that all of these devices are of materials which have the same characteristics on the microscale, to do this.

This is possible, but only with a very small yield today, and it is believed that the limit is here, not in terms of what we could do, but in terms of what we can do now. A very large computer on a good-sized missile will have 2000 individual integrated circuits, which means that about 20, 30, or 40 thousand devices can be accommodated in approximately 2 g of silicon. However, the end is not here. We have a number of devices waiting on paper and proven on fundamental grounds which we cannot produce, because the requirements on the homogeneity are even greater than today's. High sensitivity detectors, for instance, which require very high controlled impurity distribution, cannot be produced today. There are instances where we require very high concentration on what we want to put into the material; but, in order to do that, we require very high thermal gradients in the metal from which we grow it. In simple terms, this means that we have to impose on the liquid very high thermal gradients, which are impossible to maintain on earth.

What can be done on a microscale in space actually – not on a speculative basis? If we take a crystal of silicon and look at the outside, it looks very heterogeneous, not at all uniform. You see striations and heterogeneity. But out of that crystal, we must take sections to prepare the integrated circuit I was referring to before. Thus, it is no wonder that the yield of some of these devices is extremely small today.

Let us open up the crystal now and look further into it. Under higher magnification we would see the striations become very pronounced. If we magnify further to 1000 times, we would see that between the lines of striation there are many, many finer lines. Thus, at about 7 μm resolution you see many, many lines in between two striations; these are strictly the results of convections that take place at the interface and, in no way, can be completely avoided.

What can we really do to understand, here on earth, that indeed these heterogeneities are due to this type convection; that is, they are because of the fact that the crystal or solid does not solidify at the same rate throughout? It is not easy to prove this, but it has been done recently. To illustrate the principle, consider a tree. If you cut a tree across and look at the trunk, the rings represent the number of years that the tree has lived. Now, if two rings are far apart, you know that the tree grew faster than in the year where the two rings are close together. That is, we have time markers here to tell us how fast or how slow the tree was growing. We can do the same thing with the crystal. We put vibrations in it, and these vibrations would be the equivalent of the rings of the years in the tree's life. And those vibrations are of constant frequencies, a year each, although it happens to be seconds. The separation of the rings of vibration is not constant; where we cannot even tell them apart, the crystals were growing very, very slowly and where they are farther apart, the crystal grew faster. We see that the rate of growth of the crystal is not really uniform, and, in fact, it changes very drastically.

Is there anything here on earth that we can do to improve this? Yes. We can decrease the convection current in two ways. One, we can turn the melt around and heat it on the top, not on the bottom; that means, from the bottom up, or you grow your crystal upside down. We certainly have done this, but you can appreciate the fact that you only can do it as a laboratory curiosity, that you cannot turn things upside down, and even then, note, you do not completely eliminate the convection configuration, only to some extent. The second method is by using a magnetic field. Most metal melts will behave like a viscous liquid if you put them in a transverse magnetic field, that is, the viscosity increases and they will be less subjected to convective currents. We have done that very simply by putting our apparatus into a magnet. If the temperature is low, we can now achieve what we would expect to achieve when there was no gravity. We achieve complete homogeneity. Why do we not do that rather than go to space? Because we are very limited, in terms of size, in terms of materials, and in terms of temperature. We achieve good results only at low temperatures. If we go up in temperature, even the magnetic fields cannot do us very much good. They can change things but cannot eliminate the problems.

What can we expect to achieve then in space? I would like to believe that, in this particular area, one need not speculate. Once there is no gravity, there will be no convection, and there will be homogeneity. But what do we do with homogeneous materials? Do we just improve the yields of the things that we can do now? The answer is No. We will increase the density of what we can do now by a large factor, but more important, we will be able to put to use theoretical schemes of devices for higher power, higher sensitivity, smaller sizes, and including devices which are so badly needed in the biological sciences, for either detection of pressure fluctuations in bloodstreams, temperature flucuations in bloodstreams, or things of that nature; not to mention the impacts of high-temperature semiconductors, like silicon carbide, zinc sulfide, zinc oxide, or exotic types of semiconductors. These exotic types are so difficult to prepare at all, in any applicable form on earth, we are today sort of bypassing them or are ignoring them outright.

I hope this report has conveyed to you some of the reasons that make us look to space, to the use of space as a truly new dimension in making materials which we can now only play with on paper. Having homogeneous materials does not have to do just with meeting the great expectations which are based on sound scientific and engineering basis. Beyond that, I believe, the implications of this type of homogeneous materials would even surpass the most far-out science-fiction imagination today.

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