SOME THOUGHTS ON DIRECTIONS IN MATERIALS SCIENCE

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It is a high honor to receive this award; especially so, considering the distinction of the first two recipients: Professor von Hippel, who pioneered brilliantly in the development and definition of Materials Science, and Dr. Baker, under whose leadership were made the great scientific and technological discoveries at Bell Laboratories during the past decades. It is not clear to me that I belong in this progression. I feel that I am in a position rather like that of a certain Linus. I'm sure that you all know of two famous persons named Linus but you may not have heard of the Linus to whom I refer. He was identified by the ecclesiastical historian Eusebius as the first Bishop of Rome following the Apostles Peter and Paul. In any event, this award indicates that some of my colleagues, rightly or wrongly, think highly of me and that is pleasant to know.

When Ken Jackson told me of the award he said that on the occasion of it I should present a talk. I thought that I might base the talk on the research of my associates and myself on the mechanism of crystal growth in covalent systems. However, Ken tactfully informed me that so technical a topic would not be quite appropriate. Instead, I should attempt something rather more cosmic or, at least, amusing. What follows will be some highly personal, and rather disjointed, views on where Materials Science is, how it got where it is and where it may by going.

It seems logical that Materials Science begin where conventional Chemistry ends. That is, it would be the science of characterizing, synthesizing and explaining ultramolecular structures. Such a definition is tidy for a dictionary but it is, perhaps, overly inclusive in that it intrudes on a number of already well developed and organized disciplines. More realistically, Materials Science is the science of the more complex features of the structure and behavior of real solids; especially those features which depend critically on the various structural imperfections - surfaces, internal boundaries, point and line defects - sometimes in thermodynamic

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equilibrium but more often in configurationally frozen states. The especial forte of the Materials Scientist is in determining the basic components of complex structures, how they act to produce the structures' responses to applied forces and thermal treatments and in synthesizing new materials which may exhibit unique responses.

Indeed, the main preoccupations in solid state science have, I think, progressed historically from the simpler and highly ordered toward ever more disordered and complex materials. Naturally, the early activity centered on the properties of ideal crystals and later on thermally excited oscillations within these crystals. When, in the early part of this century, the theories for ideal crystals had been fairly well developed it became clear that certain of the most important properties of solids - especially the transport and mechanical - could not possibly be accounted for by ideal crystal models. This realization triggered the invention of point and, later, line imperfections and their corollary models for transport and mechanical behavior. It is remarkable that these models generally achieved success by requiring that no more than one atom in a million be displaced from its ideal crystalline position. Such small deviations from structural regularity were aptly labelled "imperfections in nearly perfect crystals." As we know, the predictions of the models on the nature, density and function of the imperfections were to a remarkable degree confirmed by ingenious experimental studies in various laboratories during the late forties and early fifties. There have been, I think, few, if any, precedents where models of such complexity were so thoroughly vindicated by experience.

It has seemed to many in my generation that this whole historical phase was the golden era of Materials Science and I would like to dwell on it a bit. It was marked by a very strong impact of fundamental on applied science - which had always to be empirically concerned with complex and disordered systems - and one of its most notable features was a highly effective interdisciplinary interaction between physicists, chemists and certain groups of applied scientists. How a climate so favorable for such interdisciplinary discourse and cooperation developed is a fascinating historical problem. I think that two of the important factors in the development were the holistic training and outlook of some of the leading physicists of the period and the unusual receptivity of certain applied science groups, especially the metallurgical, to basic science.

One of the most striking manifestations of the metallurgists receptivity were the seminars initiated in the late 1940's by one of the most applications oriented of technical societies, the American Society of Metals. At these seminars several hundred metallurgists - students, teachers and technologists - assembled on the weekend prior to the Metals Congress to hear expositions by such leading solid state physicists as Clarence Zener, Frederick Seitz, Conyers Herring, Charles Frank, Harvey Brooks and John Slater as well as by eminent metallurgists such as Cyril Smith, Lawrence Darken and others.

Perhaps the metallurgists enthusiasm for basic science was partly due to the outstanding successes of thermodynamics and x-ray metallography when applied to metal processing and alloy development. Leading physicists may have become impressed with the importance and potential of Materials Science from their World War II experiences where a concerted use of various disciplines, basic and applied, was crucial to the success of certain of the major projects. Also following World War II leaders of the high technology laboratories recognized that further improvements of high performance electrical and mechanical devices might be materials limited. This realization stimulated the formation of interdisciplinary industrial research groups which played leading roles in the advancement as well as in the definition of Materials Science.

In the more recent past the center of activity in Materials Science has seemed to shift toward still more disordered systems; indeed, to solids so disordered, e.g. glasses and concentrated alloys, that they are very far removed from the "nearly perfect crystals" category. Of course, many materials in these classes have long been known and used. What is new is the emphasis on the synthesis of unique new disordered materials and more concerted efforts to understand their structure and behavior at the fundamental level.

Under ambient conditions most of the solids we study and actually use are in nonequilibrium configurationally frozen states. However, in terms of configurations or calories these frozen states are not far removed from equilibrium. In contrast, the new disordered materials - amorphous metals and semiconductors, microcrystalline solids and heavily supersaturated solutions - are in configurationally frozen states which are generally very far removed from equilibrium. Their syntheses, which are prominently featured in this conference, were achieved by exploitation of techniques such as ultra-rapid melt-quenching, ion sputtering, ion implantation and laser annealing. The general approach in all these methods is to create highly metalstable configurations and then immobilize them as quickly as possible. An alternative approach, which I have favored, is to bring the system into a metastable state after heterophase nucleants have been, as far as possible, eliminated and then immobilize slowly. This method has had some modest successes, when homophase nucleation was inappreciable, and could, I think, be more widely exploited. By whatever method they are formed, the variety in structure, composition and behavior of these new materials is so rich that they are likely to challenge and engage Materials Scientists for a long time to come. We should see, for example, much more use of the new techniques in the synthesis of new ceramic materials.

Now, as I rashly promised, I will try to guess what may happen next. It is always safe to predict that one of the major future frontiers will be surface and interface science. Various panels of experts have been saying this at regular intervals for decades. Actually, one of my early recommendations, thirty years ago, to G. E. Management was that fundamental studies of surfaces be reinstituted so that we might better understand heterogeneous catalysis and corrosion. Irving Langmuir must surely have made a similar recommendation to Willis Whitney, his director, three decades earlier. All this means that the problem of surfaces and interfaces is a very tough one, and this is not surprising considering that, typically, only one part in several million of the mass of a system is likely to be found in the interfacial regions. However, there are procedures for achieving very high interfacial densities in solids and such solids are exhibiting some striking and unexpected behavior. Also, some new high resolution techniques are being applied very effectively in surface studies. At the present rate of progress there is hope that, in the next decade, the surface problem can be removed from the critical list.

We might expect that the historical trend toward preoccupation with ever more disordered systems will simply continue but there is the problem how much more disordered can solids get. Actually, there is a class of complex materials which has been largely overlooked by Materials Scientists. These are the organic condensed systems, including polymeric and biological structures. Of course, they have not been wholly neglected and some have exhibited quite fascinating mechanical and electrical behavior. It is highly possible that these materials will come to attract a much larger share of attention than they now do.

In discussion of future directions there are those who remind us, often with good reason, that many of the old problems, even concerning ideal crystals, have not really been solved. However, such views often are swamped by the acclaim to those, who with whatever knowledge they had, pushed on to the discovery of new materials and phenomena.

In contrast, there are those who tell us from time to time that all the important problems in a field have, in principle, been solved and the field is therefore dead. So we were told by some of our solid state colleagues following the major developments of the "nearly perfect crystal" era. Yet here we all are, learning about and discussing materials - glassy metals and semiconductors, ion implanted solids - and new techniques for producing them, which were almost unheard of twenty-five years ago. Perhaps the one safe prediction is that ten or fifteen years from now there will be a conference similar to this one where many young enthusiasts, too naive to realize that all the important discoveries had been made, will be describing materials and processes that we, at present, have no inkling of.