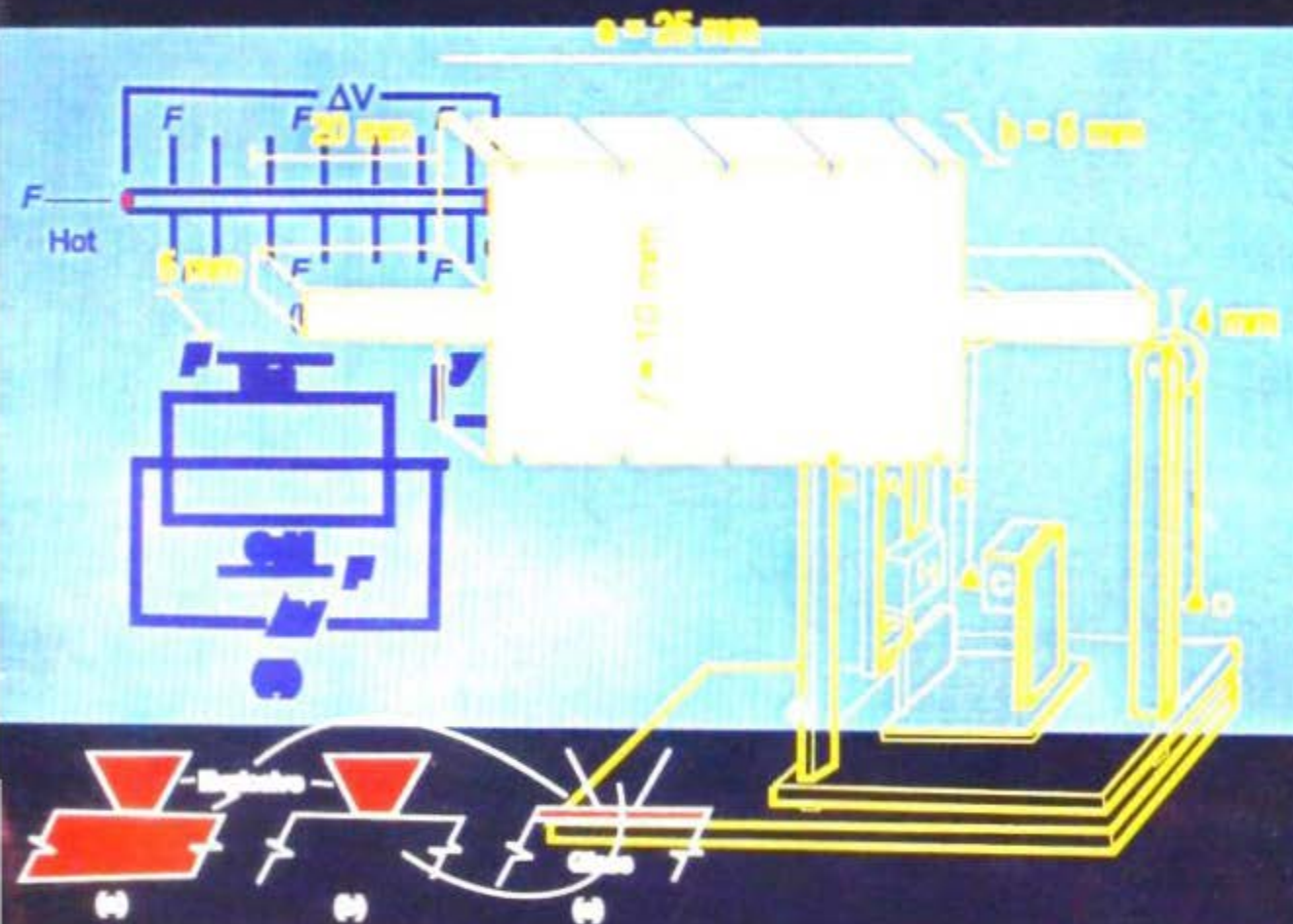




STRETCHING, SHEARING AND SLIDING IN THE SOLID STATE

*Electromechanical And
Frictional Effects In Solids*



J.K.A. AMUZU

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IN THE SOLID STATE**

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Electromechanical and Frictional
Effects in Solids

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*An Inaugural Lecture delivered at the University of Ghana on
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ABSTRACT

Our laboratory has, over the years, developed a programme of studies of the effect of mechanical deformation on the transport properties of solids. By applying tensile and shear stresses to metals and determining the changes in such properties as thermoelectric emf, resistivity and magnetic behaviour, we have made significant contributions to the basic physics underlying theories of the behaviour of these solids.

A second line of work involved studies of the tribological behaviour of solids. We have been able to show, for the first time, that the adhesion model of friction which was originally developed for metals can be applied, almost wholly, to polymers.

In this lecture, we give a panoramic account of these experiments. In a few concluding remarks, we point out what is probably wrong with solid state physics research in Ghana *vis-a-vis* glimpses of the early development of the solid state group at the Bell Laboratories.

Legon
April 30, 1998

J. K. A. A.

INTRODUCTION

Solid state physics, can be said, broadly speaking, to relate to the structure and properties of solid materials, especially in terms of the arrangement or behaviour of ions, molecules, nucleons, electrons and holes in the crystals of a substance or to the effect of crystal imperfections on the properties of a solid substance. When we speak of, for example, a solid-state stereo system today, we mean that the system does not utilize electron tubes (or valves). This manner of speaking has come as a consequence of the fact that the device that initially replaced the valve is the transistor — a device that is based on the motion of electrons and holes in solids.

As a field, solid state physics experienced one of the fastest growth-rates for an academic discipline: in the 1920s, the term solid state physics was not in use but by the mid-1970s it was the single most populated sub-field of physics. Much of the growth took place in industry. Several ground-breaking discoveries were made in industrial laboratories and among the first generation of physicists to refer to themselves as solid state physicists were Bardeen, Brittain and Shockley who invented the transistor while working at the Bell Laboratories. Indeed, it is very instructive to review the evolution of the solid state group at the Bell Laboratories because there are several lessons which we might find useful. For example, we might find something in the statement that “all successful industrial research directors have learned from experience that one thing a director of research must never do is to direct research”! We might also learn something from finding that people who were employed to work on problems relating to the telephone industry were told “you do whatever you please; anything you want to do is all right with me” and promptly embarked on research on topics apparently totally unrelated to the industry which paid their salaries: order-disorder in metals and alloys, theory of secondary emission, radar etc.

Although we do not have time now for such a review, we shall return to this theme briefly in our concluding remarks.

Our work here at Legon addresses one of the underlying concepts of solid state physics: understanding the behaviour of the Fermi surfaces of metals through a study of their transport properties. The Fermi surface is so basic to the behaviour of metals that it may well be that the best definition of a metal is that it is a solid that has a Fermi surface.

The concept of the Fermi surface in metals is intimately related to the existence of lattice periodicity which is the most fundamental property of crystalline solids. The existence of the Fermi surface is a consequence of this lattice periodicity and the fact that electrons obey Fermi-Dirac statistics. In simple terms, the Fermi surface is a mathematical construction related to the dynamical properties of the conduction electrons in a metal.

Electrons in Metals

In the simplest theory of electrons in metals, we calculate the ground-state properties of N electrons confined to a volume V . In the independent electron approximation (which means the electrons are assumed not to interact with one another), we first find the energy levels of a single electron in the volume V and then fill these levels up in a manner consistent with the Pauli exclusion principle, which permits at most one electron to occupy any single electron level. The one-electron wave function $\Psi(\mathbf{r})$ associated with a level of energy E satisfies the time-independent Schrödinger equation:

$$-\frac{\hbar^2}{2m} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \Psi(\mathbf{r}) = -\frac{\hbar^2}{2m} \nabla^2 \Psi(\mathbf{r}) = E \Psi(\mathbf{r})$$

With appropriate boundary conditions, the solution of this equation is

$$\Psi(\mathbf{r}) = \frac{1}{\sqrt{V}} \exp(i\mathbf{k} \cdot \mathbf{r})$$

with energy

$$E(\mathbf{k}) = \frac{\hbar^2 k^2}{2m}$$

where \mathbf{k} is any position independent vector, also called the wave vector. The components of \mathbf{k} are, on account of the boundary condition, of the form

$$k_x = \frac{2\pi n_x}{L}, \quad k_y = \frac{2\pi n_y}{L}, \quad k_z = \frac{2\pi n_z}{L}$$

(n_x, n_y, n_z are integers)

Thus, in a three-dimensional space with cartesian axes k_x, k_y and k_z (known as k -space) the allowed wave-vectors are those whose coordinates along the three axes are given by integral multiples of

$$\frac{2\pi}{L} \quad \text{where} \quad L = V^{1/3}$$

We often need to know how many allowed values of \mathbf{k} are contained in a region of k -space that is very large compared to $2\pi/L$ and that, therefore, contains a large number of allowed points. To a good approximation, the number of allowed points is the volume of k -space contained in the region, A , divided by the volume of k -space per point in the network of allowed values of \mathbf{k}

$$\frac{A}{\left(\frac{2\pi}{L}\right)^3} = \frac{A V}{8\pi^3}$$

Hence, the number of allowed k -values per unit volume of k -space is

$$V/8\pi^3$$

The one-electron levels are specified by the wave vectors \mathbf{k} and

by the projection of the electron's spin along an arbitrary axis which can take either of the two values $\hbar/2$ or $-\hbar/2$. Therefore, associated with each allowed wave vector \mathbf{k} are two electronic levels, one for each direction of the electron's spin.

In building up the N -electron ground state, we begin by placing two electrons in the one-electron level $\mathbf{k} = 0$ which has the lowest energy $E = 0$. We continue to add electrons successively filling the one-electron levels of lowest energy that are not already occupied. Since the energy of a one-electron level is directly proportional to the square of its wave vector, when N is very large, the occupied region will be a sphere. The radius of this sphere is called k_F (the F is for Fermi). The sphere of radius k_F (the Fermi wave vector) containing occupied one-electron levels is called the **Fermi sphere**. The surface of the Fermi sphere, which separates the occupied from the unoccupied levels is called the **Fermi surface**.

The Fermi Surface in the Noble Metals

The noble metals — copper, silver and gold — are so called because their electronic configurations bear strong resemblances to those of the noble gases — closed-shell atomic levels giving rise to very tightly-bound bands that can be considered as part of the inert ion cores while the remaining bands can be constructed by considering either a bcc Bravais lattice of K^+ ion cores to which is added one electron per unit cell or an fcc Bravais lattice of Cu^{11+} ions to which is added eleven electrons per unit cell: $Cu ([Ar] 3d^{10}4s^1)$. The elements in the periodic table which bear very close resemblance in terms of electron configuration to the noble metals are the alkali metals (compare $K ([Ar] 4s^1)$ to the configuration of Cu given above). In the case of potassium (and the other alkalis), the extra electron is accommodated by filling half of a band that is free electron-like. In the case of Cu (and the other noble metals), at least six bands are required to accommodate the eleven additional electrons.

The Fermi surface for a single half-filled free electron band in an fcc Bravais lattice is a sphere entirely contained within the first Brillouin zone, approaching the surface of the zone most closely in

the $\langle 111 \rangle$ directions. (The Brillouin zone is the polyhedron in momentum space whose boundaries define the positions of energy gaps in the band structure of metals.) The Fermi surfaces of all three noble metals are closely related to the free electron sphere; however, in the $\langle 111 \rangle$ directions, contact is actually made with the zone faces and eight "necks" reach out to touch the eight hexagonal faces of the zone, but otherwise the surface is not grossly distorted from spherical (Fig. 1).

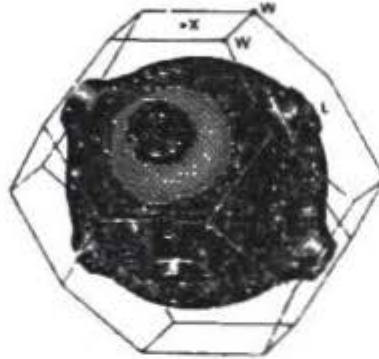


Fig. 1: The Fermi surface of copper showing necks where it reaches out to the zone boundary.

Source: From Elliott, R. J. and A. F. Gibson (1978). *An Introduction to Solid State Physics and its Applications*, ELBS and Macmillan, London and Basingstoke, p 107.

Stress Dependence of the Fermi Surface

Elastic stresses alter the topology of the Fermi surface. Experimental investigation of the stress dependence of the surface may provide a rather critical test of the theoretical models used in describing a metal. Since the electronic transport properties of metals are, to a large extent, determined by their band structures and the shape of their Fermi surfaces, information on the topologies of the Fermi surface can be obtained by measurements on these properties — electrical conductivity, the Hall effect, magnetoresistance, thermoelectricity etc. While the study of these bulk or macroscopic properties may not be particularly sensitive to the fine details of the shape of the Fermi surface, it is nevertheless possible to use these properties to obtain some general indications of trends in the topology of the Fermi surfaces of metals in a given group or row of the periodic table.

The Longitudinal Piezothermoelectric Effect

Here at Legon, our experiments have been concerned with the variation of thermoelectric power with stress — the piezothermoelectric effect. Early studies of this effect were mainly concerned with the ability to correct for the effect of pressure on the output emf of thermocouples in pressure vessels. Our first experiments obtained the longitudinal piezothermoelectric coefficient, π_L , which is a measure of the change in thermoelectric power per unit tensile stress (i.e. stretching force) per unit temperature gradient. We found, for example, that when these coefficients for the noble metals were arranged in increasing order of magnitude, we obtained the same sequence as obtained in 1969 by Luckvick for the relative changes in the Fermi surfaces on the application of uniaxial stress or hydrostatic compression. However, we did not make any attempts to establish a quantitative relation between our coefficients and changes in the Fermi surfaces because our set-up (Fig. 2) was so simple that we shrank from venturing so far afield. Wires of diameter between 0.3 mm and 1 mm were stretched in a simple holder. One end was fixed and the other passed over a pulley so that weights could be attached. Junctions were made with unstretched pieces of the same wire. One junction was kept in a hot sandbath and the other was held in a bath of melting ice. The unstretched sections of the wire were joined to galvanometer leads in a constant temperature bath.

To be able to detect changes in the thermoelectric emf, we needed a measuring system sensitive to one-hundredth of one-millionth of a volt (i.e. 10^{-8} V). We achieved this by designing a rather ingenious galvanometer amplifier system (Fig. 3).

The thermoelectric emf is fed into the galvanometer, G1, which is about 1 m away from the galvanometer lamp L1. The light spot is received on two photocells mounted side by side in a blackbox C1 which is held on the scale carried by L1. The output of the cells in C1 is fed into a second galvanometer G2. The lamp L2 also carries a box of photocells C2 the output of which is then received on a recorder R. This way, the very small voltages from the thermocouples are

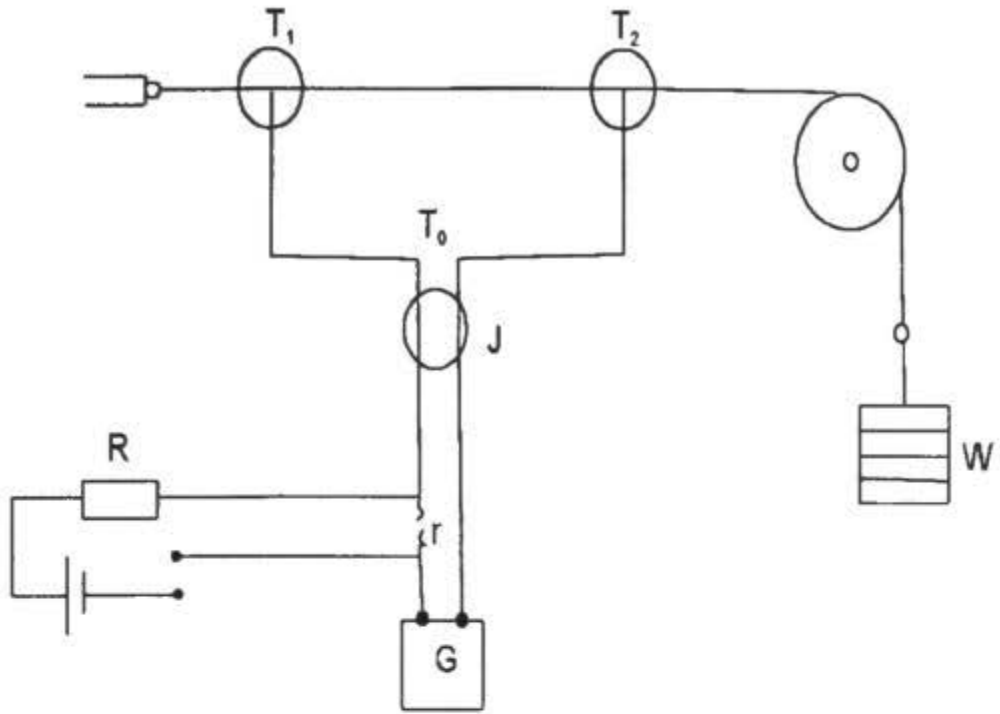


Fig. 2: Experimental set up for the measurement of the longitudinal piezothermoelectric coefficient, Π_L .

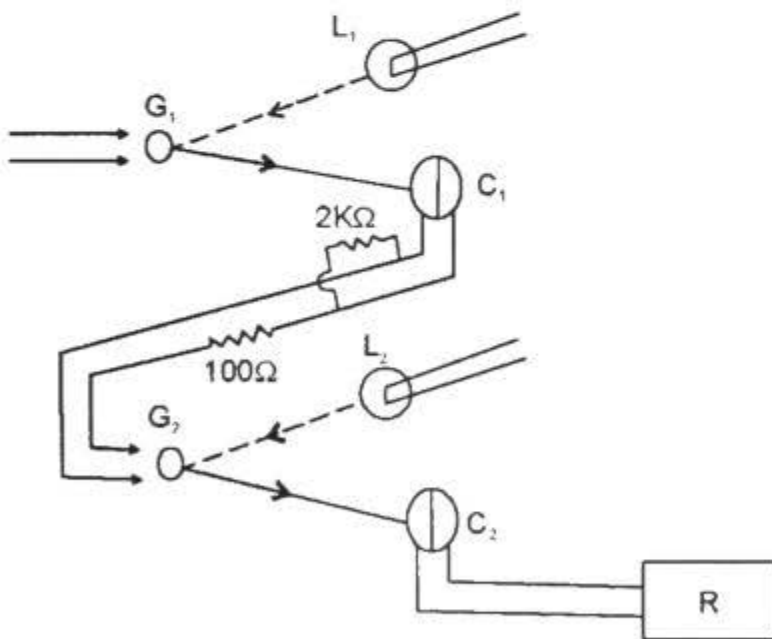


Fig. 3: Galvanometer amplifier system for measurement of thermoelectric emf

magnified several-fold and can be measured. The system is calibrated by feeding into G1 known voltages of the order of 10^{-8}V and reading the deflection on the recorder. Using this system, we carried out a systematic measurement of π_L for several metals chosen from different rows and columns of the periodic table of the elements (Fig. 4). We are still trying to explain, in terms of the electronic configuration of the elements why π_L seems to increase as we go down a column in the periodic table and to decrease as we progress in a row.

25 V	27 Co	28 Ni	29 Cu
41 Nb			47 Ag
73 Ta			79 Au

Fig. 4: A diagram showing rows and columns of a section of the periodic table and the elements which were studied.

We did decide, later in our experiments, to venture far a field and relate our coefficients to the quantitative changes in the Fermi surfaces of the noble metals. Since our samples are polycrystalline, the relative change of the area of the surface with stress, $(\Delta A/A)/(\Delta A/\Delta\sigma)$ that we determined are averages over all directions of uniaxial stress. The fact that our values are close to measurements by other workers, using different techniques such as the de Haas-van Alphen effect, on the neck regions of the surface is very surprising indeed. This is because since most of the Fermi surface area is belly-like, we expect the belly to dominate an average of $(\Delta A/A)/\Delta\sigma$ over the Fermi surface, rather than the neck.

It has been said that outstanding unexplained features of the transport properties of the noble metals are all the more distressing since detailed knowledge of the Fermi surfaces of these metals has deprived us of the convenient excuse that with a complete under-

TABLE 1

Relative Changes in the Fermi Surface Areas, $\Delta A/A$ and Relative Changes in the Cross Sectional Areas of the Fermi Surface Necks, $\Delta A_n/A_n$ per unit stress (in units of $10^{-11} \text{ N}^{-1} \text{ m}^2$)

<i>Investigation Method</i>	<i>Relative Change</i>	<i>Cu</i>	<i>Au</i>	<i>Ag</i>
DHVA effect (Slavin 1973)	$\frac{\Delta A_n/A_n}{\Delta\sigma}$	8.8 ± 0.8	11.9 ± 1.1	22 ± 6
DHVA effect (Shoenberg and Watts 1967)	$\frac{\Delta A_n/A_n}{\Delta\sigma}$	0.9 ± 1.5	7.4 ± 1.2	15 ± 1
DHVA effect (Gamble and Watts 1972)	$\frac{\Delta A_n/A_n}{\Delta\sigma}$		12.3 ± 1.2	—
TEMF (Amuzu, 1981)	$\frac{\Delta A/A}{\Delta\sigma}$	3.53 ± 0.6	6.15 ± 0.8	6.19 ± 0.3
TEMF (Amuzu and Addoh, 1982)	$\frac{\Delta A/A}{\Delta\sigma}$	2.88 ± 0.5	6.10 ± 0.2	9.70 ± 0.9

standing of the band structure will come the answer to the puzzles. Clearly, much remains to be done.

The Shear Piezothermoelectric Coefficient, π_s

It is not only by stretching solids do we alter the topology of their Fermi surfaces; shearing them and applying hydrostatic pressure also achieve similar results. We can define three piezothermoelectric coefficients: π_v corresponding to hydrostatic pressure (change of volume); π_L corresponding to uniaxial tension, the measurement of which we have already described; and π_s , the shear effect. Fig. 5

illustrates the different orientations for the measurement of these coefficients:

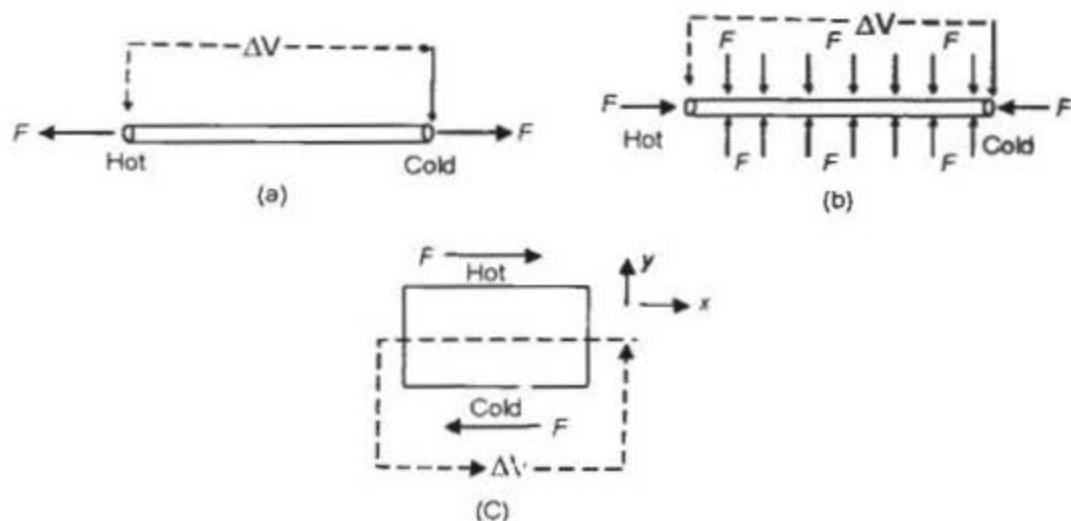


Fig. 5: The different orientations for the measurement of the piezothermoelectric coefficients. (a) The longitudinal effect (π_L): a wire stretched in the x direction, TEMF measured in the same direction (b) The pressure (or volume) effect (π_V): a wire is subjected to hydrostatic pressure and the TEMF measured. (c) The shear effect (π_S) application of shear in the xy plane, TEMF measured in a direction transverse to temperature gradient.

Tinder (1972) has given the constitutive relation for the coefficients which completely specify the thermoelectric power tensor π_{ijk} . In matrix subscript notation, this relation is

$$S_j = \pi_{ijk} \sigma_{kl}$$

where S_j is the thermoelectric power tensor and σ_{kl} the stress tensor. For the longitudinal piezothermoelectric effect this relation becomes, for cubic crystals

$$\frac{\Delta S_1}{\sigma_1} = \pi_{11} + 2 A F$$

where the subscripts ij and kl have been unfolded according to the

scheme 11 is 1, 22 is 2, 33 is 3, 23 is 4 etc. in agreement with common practice. A is the piezothermoelectric power anisotropy factor and F is the orientation factor. For polycrystalline isotropic crystals, $A=0$ so that the changes in the thermoelectric power for the various types of stress can be written as

$$\Delta S_V = -(\nu + 3\eta) P = -\pi_V P$$

$$\Delta S_L = (\nu + \eta) \sigma = \pi_L \sigma$$

$$\Delta S_S = \nu \sigma = \pi_S \sigma$$

Where $\eta = \pi_{12}$, $\nu = \pi_{44}$, and $\nu + \eta = \pi_{11}$

$$\text{Hence } \pi_S = \frac{3}{2} \pi_L - \frac{1}{2} \pi_V$$

Bridgman has measured π_V for several metals including the noble metals. Measurement of the shear coefficient presents serious experimental difficulties and is very seldom attempted. Our two attempts made 14 years apart can only be regarded as first attempts to establish the effect and obtain values of π_S which reflect the order of magnitude. The difficulty lies, essentially in the application of shearing stresses to a specimen. Fig. 6 shows the diagram of our apparatus for doing this.

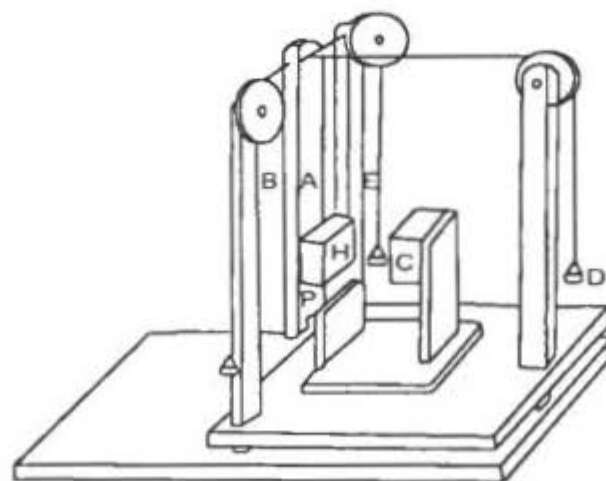


Fig. 6: Diagram of the apparatus for the application of shear forces to specimen.

The essential parts of the machine are the movable central arm (A), the hot box (H) and the cold box (C). A can move about the pivot P. It also carries the box (H) which can be heated electrically. Facing H is a vertically-mounted plate which carries the box (C), through which cold water can be circulated. Each box has a centrally-placed tooth which fits into one of the several notches cut on the specimen as shown in Fig. 7. This is to prevent slipping between the specimen and the boxes. The remaining notches on the specimen carry copper-constantan thermocouples with which the temperature gradient generated across the specimen can be measured. The hot and cold boxes and the specimen are pushed tightly together by the application of a 5 kg load at D. The fixed arms (B and E) carry pulleys and by applying loads to wires going over these, the central arm can be pulled either to the right or to the left. The hot and cold boxes are made of copper and insulated from the rest of the steel machine.

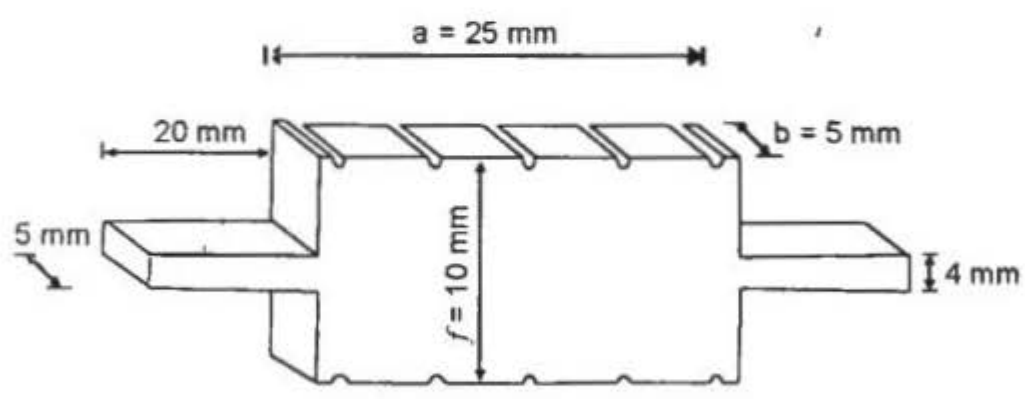


Fig. 7: Diagram of specimen shaped into a rectangular block. The notches prevent slipping in the shearing machine and also carry thermocouples.

A comparison of our measured values and the calculated values for π_s as in Table 2, shows that our method is indeed a viable way to proceed.

TABLE 2

Piezothermoelectric Coefficients for Copper and Silver

	π_L	π_V	π_s cal	π_s exp
Cu	3.61	2.9	4.0	3.4 ± 0.8
Ag	8.1	8.3	8.0	6.5 ± 1.1

The values are in $10^{-17} \text{ VK}^{-1} \text{ m}^2\text{N}^{-1}$.

It must be pointed out, however, that our results were very variable. This could be due to the suggestion that the effect could be quite different for the two types of shear corresponding to the elastic constants $\frac{1}{2}(C_{11} - C_{12})$ and C_{14} . Variations in the orientation distribution of the crystals in the polycrystalline specimen might then account for the variability of the measurements. It would, therefore, be desirable to perform these experiments on single-crystal specimens, although, clearly the measurements would be extremely difficult.

We have already pointed out that the initial experiments on the piezothermoelectric effect were mainly concerned with the ability to correct for the effect of pressure on the output emf of thermocouples in pressure vessels. Of course, there is nothing new about efforts to solve technical problems leading to studies in basic science because, needless to say, that is how it has always been. However, it is still a curious thing that a completely different technical problem has lead us to the investigation of the applicability of a theory of metallic behaviour to other types of solid. This investigation has involved experiments in which, this time, we slide solids over other solids or over themselves. We shall now discuss these experiments.

Friction in Polymers

Sliding friction is one of the oldest problems in physics and certainly one of the most important from a practical point of view. The ability to produce durable low-friction surfaces and lubricant fluids has become an important factor in the miniaturization of moving

components in many technological devices: magnetic storage, recording systems, miniature motors and many aerospace components.

It is now generally accepted that certain aspects of the friction of polymers (or plastics) may be explained in terms of the adhesion mechanism originally developed for metals. According to this model, when two surfaces are placed together, intimate contact occurs at the tips of the asperities which are "crushed down" until their cross-section is sufficient to enable them to support the applied load. Strong adhesion (or cold welding) occurs at these regions and the frictional force is essentially the force required to shear the junctions formed.

Now, all surfaces are generally covered with thin films which normally have a profound influence on the friction and wear of contacting solids. Solid film lubrication and boundary lubrication are critical to processes involving sliding parts and several experimental techniques for studying the shearing of thin films have been developed. We have also developed a simple way to do this — we study the shearing of polymeric films deposited on hard substrates, such as glass by moving a slider over them. This is because many aspects of relative movement between lubricated contacts may be considered as the shearing of polymeric films or the sliding of such films over each other. Since lubricant oils are almost invariably organic, when sliding metallic surfaces are separated by a layer of lubricating oil films, organic material may be either absorbed or chemically formed at the surfaces and in many cases these layers may be regarded as thin films of organic polymers.

Also lubricant oils may contain viscosity-improvers many of which are polymeric-based in which case these additives may adsorb at the interface. Polymers formed *in situ* where monomer polymerizes on the hot surfaces of the contacting metals can also act as lubricants. It appears, therefore, that a study of the shear properties of thin films of organic polymers is a useful way of attempting to model the energy-dissipating processes of boundary lubrication.

Further, thin solid films have found widespread use in modern technology. One important application involves the use of thin layers of both organic and inorganic materials as solid-film lubricants. Such lubricants are used where conventional oils or greases are unsatisfac-

tory, especially where the liquid would be lost by creeping or evaporation (as at high temperatures or high vacuum) or would be an explosion hazard or a source of contamination.

The adhesion model of friction originally developed for metals assumes that the energy of sliding is dissipated in a narrow zone close to the interface because the shearing of the adhesive junctions occurs in a very thin surface layer which is about 100\AA thick. Thus, if the shear strength of the junction is τ , the frictional force can be written

$$F = \tau A$$

where A is the real area over which the surfaces are in contact. If the deformation of the contacting asperities is entirely plastic, then

$$A = W/P_0$$

where W is the normal load and P_0 the flow or plastic yield stress of the softer material in the combination. Thus,

$$F = \frac{W\tau}{P_0} \quad \text{or} \quad = \quad \mu \frac{\tau}{P_0}$$

where μ is the coefficient of friction. This relation shows that if we know the shear strength of the thin film and the contact pressure, we can obtain its coefficient of friction. However, our work and those of others show that the shear strength, τ , of a polymer film is related to the mean contact pressure, P , to a good approximation, by

$$\tau = \tau_0 + \alpha P$$

where τ_0 and α are constant for a given temperature and sliding speed. It is interesting to note that the pressure coefficient, α , is the limiting value of the coefficient of friction at high normal loads. Since the limiting condition obtains when $(\tau_0/P) \ll \alpha$.

$$\mu = \frac{\tau}{P} = \frac{\tau_0}{P} + \alpha$$

Now, when a bulk polymer is slid on either itself or on a hard counterface, the contact pressure is not very different from the mean yield pressure of the polymer, P_0 , so that under this condition we can rewrite the friction equation as

$$\mu = \left(\frac{\tau_0}{P_0} \right) + \alpha \quad \text{or} \quad = \frac{\tau(P_0)}{P_0}$$

where $\tau(P_0)$ is the value of τ at P_0 . In order to make any headway in showing that the adhesion model of friction is applicable to polymer friction, we have to make a crucial assumption. This is that when the bulk polymer is slid on a hard counterface or on itself the shear strength of the adhered region is the same as the shear strength obtained when a thin film of the polymer is sheared between rigid substrates at contact pressure P_0 . If this is so, then we can use data from our shear strength experiments on thin films to compute the coefficient of friction which we can then compare to the coefficient from conventional sliding experiments on the bulk materials. Should the thin film work yield values of μ which are the same as those obtained from measurements on the bulk materials, we would have developed a powerful tool. The reasons for saying this are as follows: friction measurement on certain classes of materials, a good example of which are explosives, is a tricky undertaking and differs somewhat from measurement on other materials. In general, it is necessary to study very small amounts of material. This restriction is brought about by the fact that it is often not possible to grow large enough single crystals, and in addition safety considerations require that only small amounts of material are used. This constraint often necessitates the adoption of experimental procedures which measure the frictional force indirectly. On the other hand, the film technique which requires only small quantities of the material constitutes a direct way of measuring the friction.

The comparisons for the computed coefficients of friction according to the equation

$$\mu = \left(\frac{\tau_o}{P_o} \right) + \alpha = \frac{\tau(P_o)}{P_o}$$

and the experimentally-observed values for a number of polymers are made in Table 3.

TABLE 3

Computed and Measured/Coefficients of Friction for Some Polymers

Polymer	P_o (Pa)	$\tau(P_o)$ (Pa)	τ_o (Pa)	τ_o/P_o	α	$\frac{\tau_o}{P_o} + \alpha$	$\frac{\tau(P_o)}{P_o}$	μ_b	μ_g
LDPE	1.53×10^7	8.0×10^6	6.0×10^6	0.39	0.14	0.53	0.52	0.52	0.42
HDPE	3.90×10^7	7.0×10^6	2.5×10^6	0.06	0.10	0.16	0.18	0.15	0.08
PTFE	2.27×10^7	3.0×10^6	1.0×10^6	0.04	0.08	0.12	0.13	0.16	0.13
PP	4.75×10^7	1.25×10^7	5.0×10^6	0.10	0.17	0.27	0.26	0.26	0.26
PMMA	2.68×10^8	1.10×10^8	1.0×10^7	0.03	0.36	0.39	0.42	0.36	0.41
PVC	1.01×10^8	4.80×10^7	-9.0×10^5	-0.09	0.57	0.46	0.48	0.55	0.54
PS	1.39×10^8	6.5×10^7	4.0×10^6	0.03	0.45	0.48	0.47	0.42	0.45

It can be seen that, in general, the agreement between $\left(\frac{\tau_o}{P_o} \right) + \alpha$, $\tau(P_o)/P_o$, μ_b and μ_g for each polymer is good; μ_b and μ_g are the coefficients of friction obtained when the bulk polymer is slid on itself and on a smooth glass substrate respectively. The close agreement between the computed coefficients of friction and the observed values supports the assumption that in the sliding of the bulk polymer energy is dissipated primarily within a thin region close to the interface.

We have carried out studies on the friction of several explosives

in order to demonstrate the versatility of our thin-film technique. Three approaches were used to measure the coefficient of friction when single crystals of explosive are slid over each other: (1) the direct method of sliding single crystal on single crystal, (2) sliding single crystals on smooth glass surfaces, and (3) depositing the crystals as thin films on glass surfaces and then sliding the surfaces over one another. Fig. 8 shows schematic diagrams of the three sliding configurations.

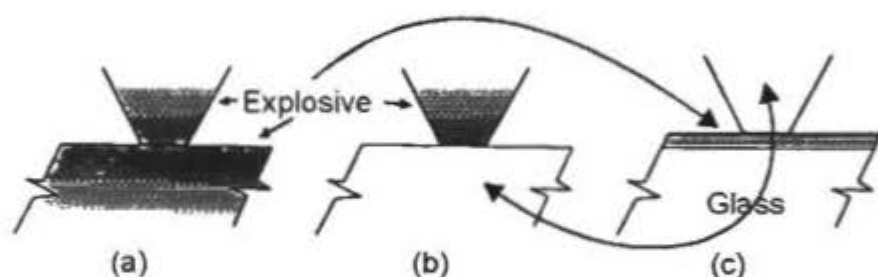


Fig. 8: Schematic diagram of the sliding configurations: (a) single crystal on single crystal, (b) single crystal on glass; (c) thin film between glass surfaces.

We have shown that the thin-film technique is capable of predicting accurately the coefficients of friction obtained by the other techniques, as shown in Table 4.

This is consistent with the adhesion model of friction, which supposes that the energy of sliding is dissipated in a narrow zone close to the interface, and which was originally developed for metals. To be sure, there are several differences between the friction of polymers and the friction of metals, although the adhesion model appears to explain the main features of both. Perhaps the most important of these differences concerns the mode of deformation. In metals, deformation at the contacting asperities is plastic so that the area of contact is constant and given by $A = W/p_0$. Since polymers are viscoelastic, the real area of contact depends on both the applied load and the geometry of the surface as well as the time of loading.

TABLE 4

Coefficients of Friction Determined for Three Sliding Configurations
(in Fig. 8)

Column	1	2	3	4	5	6
Crystal	μ	τ_0	α	μ_{cal}	μ	$-(1-m)$
PETN	0.40	-5.0×10^6 Pa	0.45 ± 0.05	0.38 ± 0.02	0.40	0.39
HMX	0.55	—	—	—	—	0.29
RDX	0.35	—	—	—	—	0.26
AgN ₃	0.40	1.01×10^7 Pa	0.42 ± 0.01	0.44 ± 0.02	—	0.37
Pb(N ₃) ₂	0.28	2.9×10^6 Pa	0.26 ± 0.04	0.26 ± 0.04	—	0.28

Column 1. μ , coefficient of friction in configuration (b) at high loads; marked plastic deformation of the contact occurs.

Column 2. τ_0 , constant measured at 20 °C; configuration (c).

Column 3. α , constant measured at 20 °C; configuration (c).

Column 4. μ_{cal} , calculated coefficient of friction at high loads.

Column 5. μ , coefficient of friction for single crystal on single crystal

Column 6. for smooth elastic contacts $(1-m) = -0.33$.

The sliding friction, F , in this case, can be written as $F \propto W^n$ where n is termed the load index. This means that the area, A , follows a law of the type $A \propto W^n$. For the simplest case of a single contact area between crossed cylinders, or a sphere on flat, elasticity theory gives $n = 2/3$ so that the load index of the coefficient of friction which is given by $n-1$ is $-1/3$. We have carried out studies on the load index of several polymers in a series of experiments in which very smooth hemispherical polymer surfaces were slid on smooth glass slides in an attempt to model the sphere on flat configuration. The polymer hemispheres were prepared in moulds made by pressing steel ball bearings of known diameters into aluminium blocks. The most significant finding in these experiments is the strong dependence of the indices on the radii of the sliding hemispheres. Additionally, the observed experimental indices agree rather closely with values computed from theory. Indeed, it has been possible to show that any differences between the experimental

and calculated values measure the degree of smoothness achieved in the preparation of the sliding hemispheres. Because our aluminium moulds used for making the sliders were carefully polished with pure aluminium oxide of particle size of about 0.05μ , the differences between our calculated and measured indices are so small as to be virtually negligible.

Friction Studies on Road Surfaces

No doubt, these results constitute important and basic contributions to the adhesion theory of sliding friction. However, we have also tried to apply our expertise in friction work to a problem which all of us can appreciate.

For safe motoring, it is imperative that there is adequate traction between the tyre and the road surface. The greatest threat to the achievement of this requirement arises under wet conditions where it is possible for films of water to form between the tyre and the road, thereby reducing the traction. The coefficient of friction at the contact between tyres and a dry road can achieve values as high as greater than 1. However, on a poor-quality wet road, the coefficient can be as low as 0.2. Clearly, an increase in the wet friction will contribute to driving safety. Tyres and roads are, therefore, designed to dissipate this water at the contact patch as quickly as possible. The coarse roughness of road surfaces and the tread patterns on tyres provide some drainage for the water at the contact region.

The details of the behaviour of one tread pattern differ from those of another. However, the main function of the patterns is to break up the area of contact between the tyre and the road so, that only small regions of tyre and road are in contact at any instant. Consequently, any water film that may be trapped between the tyre and the road is squeezed out. Additionally, fine cuts and edges in the tread pattern facilitate the wiping away of the water film as the wheel rotates. For example, in one test, the coefficient of friction increased from 0.35 when a smooth tyre was slid on a road surface to more than 0.6 when a tyre of similar rubber but with a patterned tread was slid on the same road surface.

A second approach is to use rubber which has high hysteresis losses in the manufacture of tyres. The elastic recovery of the rubber after it has been grooved by the protuberances on the road surface involves hysteresis losses of elastic energy and the higher these losses are, the greater the frictional resistance.

The third approach to an increase in wet friction involves the modification of the road surface. It has been shown that there must be adequate space for the trapped water to escape between the projecting stone chippings when the tyre passes over the surface and that the shape of the projecting pieces of stone determines the extent to which they can penetrate the water film and make dry contact with the tyre.

We have studied the efficiency of various road surfaces in providing the drainage for water at the tyre-road contact region. The study involves the determination of rates of drainage of water using a large cylinder, open at both ends with one end fitted with a rubber lip. The cylinder is placed vertically on the road surface with the rubber resting on the road. A load applied to the cylinder presses the rubber into the road surface. For sufficiently large loads the bottom end of the cylinder is completely sealed so that no leakage of water in the cylinder occurs. For smaller loads, measurements are made of the volume of water that leaks from the cylinder per unit time. A simple mechanical surface profilometer was used to explore the geometry of the road surfaces studied. Various road surfaces on the Legon campus were selected for study, the choices being such that a range of surfaces, from the very fine texture (asphalted road surface) to the very coarse (with lots of protruding large chippings and some loose pebbles) was covered.

Our results indicate that fine-textured road surfaces (for example, asphalted roads) are the most hazardous when wet because of their inability to drain efficiently the water trapped in the contact patch at the road-tyre contact. Coarse-textured surfaces are the safest when wet.

It is mildly surprising, therefore, that modern road engineering appears to have a preference for asphalted roads. The reasons for the

preference are, presumably, found in the attractive advantages these roads offer:

1. they prevent water from penetrating to underlying material and hence have longer life than coarse-textured roads;
2. the wear rate of tyre on asphalted roads is relatively low;
3. asphalted roads make motoring a comfortable undertaking.

CONCLUDING REMARKS

I have attempted to give you what may be described as a panoramic account of our work in the Department of Physics at Legon. Solid state physics occupies a special place in the Department. Ever since the first students of our former Head of Department (and former Dean of the Faculty), Professor Alan Nunn May began to return from taking their PhDs in the mid-1960s the percentage of the faculty working in solid state physics maintained a steady increase and now stands at 40 per cent. Professor May set up the Solid State and Metal Physics Research Group in 1962 under a Special Professorship scheme to train young Ghanaian scientists in the physics of metals and other solids.

The special professorship that Professor May held allowed him to offer generous incentives in the form of holiday jobs to those of us whom he had earmarked for further training. Most times, all that we were required to do in order to draw a salary at the end of the month was to, as he himself put it, mess about in the laboratory. Alas, in the present times, this is completely out of the question. Is it any wonder then, that we cannot attract promising students to remain in the University and take higher degrees in the "dry" areas such as Mathematics and Physics? The programme was directed especially at materials such as diamonds and semiconductors which were deemed to be important for Ghana's industrial development. A small but active

group of young scientists flourished under Professor May. The work on diamonds promised to provide a means of testing the theories of their formation in the earth's crust and the theoretical work on the melting of metals was meant to lead to a clearer picture of this fundamental phenomenon. Of the students who trained under this programme at least six went on to obtain PhDs in prestigious universities abroad and four of them are still on the academic staff here at Legon.

The area of work that Professor May handed down to me involves studies of the effect of tensile stresses on such transport properties as thermoelectric power, resistivity and magnetic behaviour of solids. Indeed, the first post-graduate degree awarded in solid state physics after the departure of Professor May was for an aspect of my work which I have described. Another of my students is currently working for his PhD in dental materials in Manchester and he will return to our Dental School soon.

I believe I can say without fear of contradiction, that remaining active in research in solid state physics in our part of the world is not one of the easiest undertakings. The reasons for this state of affairs have become such an old song that there really is no point in singing it right now. However, I wish to state that it is indeed tragic that the fact that industry can be a catalyst for basic scientific research and in so doing place itself in a position to reap a rich harvest in the results of such research appears to be completely lost on us here in this society. I have, at the beginning of this lecture, alluded to the goings-on at the Bell Laboratories at the time of the evolution of the solid state group there. The technological needs of the telephone industry led to in-house research. The inevitable interactions of this in-house research group with scientific researchers outside its walls eventually focussed some of the in-house's principally basic technical studies on even more fundamental scientific problems. If we are looking for proof that the manner of procedure adopted in those early days at the Bell Laboratories is a valid way of doing things, we only need to remember that that is how the transistor was discovered. In the process of attempting to build an amplifier to replace the mechanical repeaters in

use for long distance telephony, the in-house researchers collaborated with other researchers working on such basic phenomena as electron transport in solids which led to the transistor. Additionally, the strategy of resorting to in-house research in dealing with problems directly pertinent to it saved the industry from the necessity of buying patents from other institutions or individuals. I believe there is a lesson here for our industries.

The shift in the focus of some of the in-house research onto fundamental scientific problems was aided by a phenomenon which, to me, is also not very well appreciated in our part of the world. This is the understanding that creative scientists need freedom to speculate and explore intellectually and to communicate with colleagues working on similar problems. This is the reason why it did not worry the company that some of the results of the work of its scientists might be employed outside the company. Again, active participation and competition in the larger scientific community were recognized as the most effective means to achieve and maintain awareness of scientific frontiers. The tradition of individual visits to other laboratories developed in this period. Academic institutions integrated the industrial researchers into their programmes, inviting them to lecture on how fundamental science could be applied to engineering problems. The point here is that science (or more specifically, applicable science) has never and cannot be expected to flourish in isolation. It is a cooperative effort between the researchers and those who expect to employ the results of research.

I do not wish to suggest here that Ghanaian scientists should ask for nor that the funding system can afford such blank cheque as issued to the early solid state physicists at the Bell Laboratories. (Remember some of them were told "you do whatever you please; anything you do is all right with me"). But I do wish to suggest that there are circumstances in which the blank cheque is the only viable route to the solution to a problem. Some of us who are engaged on studies in basic scientific research sometimes run out of patience for those who dismiss our efforts because they do not see us solving any of the society's problems. To be sure, the results of our research which

I have described this evening have not led to the solution of a specific problem of the Ghanaian society. However, they have been published in internationally-available journals for use by the world scientific community. I believe that because of this fact we have not done more or less than what the scientists at the Bell Laboratories had recognized as a necessary requirement for true scientific research.

It is tempting to complain about the conditions under which we are forced to operate as researchers and forget that we are, at the same time, teachers. It is distressing that we have been reduced, by our circumstances, to under-achievers as teachers. We appear not to be able or willing to make scientists out of bright young Senior Secondary School graduates whose elective subjects are in agriculture. When a colleague and I came from Keta Secondary School to do the Preliminary Course in Science in October 1966, we had not seen, never mind handled, pipettes and burettes in our young lives, because our school did not offer Additional General Science or the individual science subjects; and if you did just General Science you did not have to take practical classes! That colleague of mine is now a Professor of Chemistry at Cornell University and is among the best-known scientists in the US. It appears to me that one of the most pressing tasks we have is to work to re-establish the conditions that made it possible for this University to make Professors of Chemistry and Physics out of people like my colleague and me.

I suspect that before Professor Kofi Anyidoho's Inaugural a few months ago, many of us thought that certain matters did not belong in an Inaugural. I am not thinking about the famous Fiadzigbe scenario here (Anyidoho 1997), but I am thinking about the fact that sitting in this audience is my elder brother who gave up his allowances at teacher training college so that I could go to secondary school; I am thinking of our mother (may God keep her) who slaved so I did not miss a father who died before I was born (let me remind you that this is not new information, the A in my initials J. K. A. has always proclaimed the fact) and my sisters who remain in the little village, and who slaved with our mother. The latter phases of my struggle up this rostrum were sustained by my wife who was joined later by our children and I

thank Professor Anyidoho for making it possible for me to acknowledge their roles as a I stand on the rostrum I had been seeking.

This a very fine institution we have here at Legon. I have long taken the view that one of the reasons for this fineness is that we have, over the years, employed equipment, which are so simple and so old that a Japanese diplomat, on a visit to our laboratory once, observed that those might very well be the same meters used by Maxwell himself (you must recall here that this is the same Maxwell who died in 1879!) to achieve results which allow us to stand in the community of academics if not with our chests fully out, certainly not with our heads bowed.

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