Materials Research : Key to Progress in Electronics

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Materials Research — Key to Progress in Electronics

By *R. W. Peter,* Princeton

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1. Introduction

The aim of technology has been through past centuries, and will be in the future, to enlarge man's capabilities by increasing his control over "nature" for his purposes. Progress in technology has provided him with means to see and hear farther, travel faster, and produce more goods and services per man hour. Simplifying reality grossly, one can attribute this progress primarily to the fact that man has learned to build more "intelligence" into machines which have available increasing amounts of power for performing useful functions.

Many branches of industry are involved in furthering "machine intelligence"—through mechanization and automation—and in increasing power production. Of all industries, however, electronics possesses the highest inherent potential to become the major factor in future technological development. It is not astonishing in this light that the electronics industry today is the fastest growing major industry. Fiftieth in rank before the last world war, electronics is now in the fifth place among American industries in value of goods and services sold[1]). More and more industries and businesses are adding electronics laboratories, departments and divisions to their engineering activities and product lines. The newer dynamic industries, such as the aviation industry, are beginning to compete with established electronics firms in their technical and business areas; but also the older and more conservative industries—such as steel and food producers—are looking to electronics as the way to accelerate progress.

2. Spotlight on Materials Research

In this unparalleled, almost explosive, expansion and invasion of electronics during the past two decades, materials research has come into a key position. The basis of this lies in the recognition that the key to man's control over nature's unlimited resources rests in his ability to control matter on the atomic and molecular scale. Evidence proving this proposition surrounds us in our daily life. The most impressive and awesome illustration is the development of nuclear power generation, clearly a feat which depended upon man's control of matter on the atomic level. Less conspicuous evidence is provided by television and radio. Color television would not be a reality had it not been possible to create phosphors with adequate luminescent brightness in the three primary colors. Portable radios would not yet fit into a shirt pocket, had not tiny transistors been developed to perform the function of vacuum tubes.

Research programs in many leading electronics laboratories reflect this shift in emphasis since the last world war: materials research activities have expanded more than other branches of research and have more than kept pace with the growth of the industry.

Why has the need for new materials and research in this field so suddenly gained this pre-eminent importance? Dr. *A. B. Kinzel* in his opening address at the 1959 Navy Materials Symposium[2]) pointed to the core of the situation: The cry for better materials is as old as engineering itself. However, in earlier times, the engineer who cried didn't know how far materials, such as steel, might be improved and, therefore, didn't wait for any improvements which in time came along. Today, by virtue of a better scientific training in engineering education and also due to the influx of scientists into the sophisticated engineering areas, the engineer knows of the potentialities of materials, requests improvements, and waits for them. This puts an unprecedented pressure on the respective materials research groups.

The progress, and often the success, of a whole engineering project thus may become dependent upon the advances in

[1]) According to statistical information obtained from the Electronic Industries Association and the Statistical Abstracts of the United Staates, 1959.

[2]) *A. B. Kinzel:* "Research and Materials". Proc. Symposium on Materials Research in the Navy, ONR-5, Vol. I, March 1959.

materials. A radar system, for example, may not reach expected performance because of electric breakdown in the ceramic window of the microwave power tube. Occasionally in reverse, a new discovery on the materials end of a systems project may lead to sudden advances radical enough to render all previous or competitive solutions obsolete. These "breakthroughs", though very rare, have contributed greatly to establishing materials research as a powerful key factor of progress in electronics.

3. Ultimate Objective of Materials Research

The ultimate aim of materials research is characterized most vividly by *Von Hippel's* term "Molecular Engineering"[3]). "Engineering" implies using human "ingenium" to build up materials on the "molecular" scale, employing molecules as the building blocks. The goal is to design the different functions of a system into a minimum volume of matter.

This situation represents the ultimate aim of the materials scientist. Nature has achieved this goal in many areas of building living organisms. Consider, for example, the "molecularly engineered" chromosome, blueprint for reproduction of living species. Every molecule (or gene) in a chromosome has its distinct and well-defined function and characteristics. The sum total of these molecules, uniquely defined in number, forms the complete information-storage system needed to build a replica of a species. The information content and the reliability of this reproductive system is demonstrated, for example, by the extreme likeness of identical twins[4]).

4. Status of Materials Research

It is important to keep the true meaning of the ultimate goal of materials research, namely "molecular engineering" clearly in mind. It helps one to appreciate how far even the most advanced materials research is still away from it. Also, it provides a long-range perspective needed for guiding a materials research program.

At present, we know how to control *bulk* properties of materials on a molecular scale, for example, by growing almost perfect crystals, then adding various "activators" in small amounts. We have, however, not yet learned to control the *surfaces* of such bulk materials to the same degree, neither do we know how to grow single crystal *films* of these materials. This is, clearly, still a far cry from the goal.

In this framework, the present status of materials research in electronics may—in a round-about way—be best characterized by the fact that it is performed mostly by teams of physicists, inorganic chemists, metallurgists and ceramists. Organic chemists are slowly becoming part of the materials research scene in some electronics laboratories. Biologists and physiologists (still recognizable as such) are still a definite rarity. The author ventures to say that more scientists of the latter three categories will be found active in electronics materials research by the time we can claim to have approached true "molecular engineering". Looking back, however, there is no doubt that materials science has come a long way, and we cannot help but feel enthusiastic about the progress achieved so far.

5. The Three Aspects of Materials Research

The task a materials scientist faces, when asked to provide a material with a certain desired or improved property (keeping all others the same, of course), is clearly stupendous. Consider a practical example to illustrate the situation. A semiconductor device researcher needs a material with higher carrier mobility at elevated temperature as a basis for improved, heat resistant semiconductor devices.

The first step the materials man has to face is the selection of the material which might best provide the optimum combination of desired characteristics. At his disposal is the whole periodic table of some 90 elements to play with. Combining two elements at a time leads to over 4000 combinations of which a larger fraction are mixtures and a smaller fraction are actual compounds. If he also considers ternary compounds, built up of three elements, the number of materials he can select from grows to over 100,000. The task in its full aspect is obviously fantastic. Besides some general rules and the chemical annals and handbooks, good common sense and infinite patience in trying out hundreds of variations are the best aids to the searching chemist.

There will come a time in the future when a fast computing machine will be able to supply physical data, such as bandgap, carrier mobilities etc., on a large number of simple compounds. The machine then will select the one or few best suited materials, e. g., gallium arsenide (GaAs) as the preferred binary semiconductor in our example (what the best ternary compound is, we still don't know!). Such an ambitious theoretical program is underway at RCA Laboratories[5]). The chemist, however, does not expect to be waiting for the theorist to provide the choice selection for some years to come.

Even at that time, the other two most demanding tasks will still remain with the materials scientists: the ultimate purification of the choice material, and its controlled alloying, "doping" and activating. The attitude and the talents of the scientists involved in purification have to be similar to those of a "Sherlock Holmes". The "killers" he is after, are unwanted impurities and defects in the materials. In the example of GaAs they appear to be as tough and elusive as the criminals in a perfect murder.

The third job the materials synthesis man has to perform is the one of an "artist". Highly sensitive to the resulting change, he alloys the purified elements and compounds and finally introduces the active impurities and "dopes" to bring out the desired particular quality or phenomenon. Germanium or gallium arsenide, for example, may be activated

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[3]) MIT Summer Session on "Molecular Engineering", August 1956.

[4]) It has been estimated that less than 10^6 atoms (a cube of 100 atoms on the side) are used to store one bit of information (a yes or no indication) in a chromosome. This represents a storage density at least 1000 times larger than that achieved in photographic or thermoplastic (Eidophor-type) memory systems which in turn contain about two orders of magnitude more information per cm^2 than obtained with best present magnetic tape storage systems (maximum achieved is about 10^6 bit/cm^2).

[5]) This work is an outgrowth of energy-band calculations such as, for example, *F. Herman:* Theoretical Investigation of the Electronic Energy Band Structure of Solids. Reviews of Modern Physics, Vol. 30 (1958), No. 1, p. 102–121.

to become basic material for a transistor, or a tunnel diode or for an infrared photosensitive detector.

These then are the three faces of the materials synthesis man: he must be a "cook" with good common sense and much experience, as well as many recipe books, a "detective" with imagination and analyzing power, and an "artist" with sensitivity.

Materials synthesis, however, is only part of an integrated materials research activity. The *measurements approach* which interrogates nature, and the *theoretical approach* which aims at devising a hypothesis or model, always have to join hands with the *synthesis approach* in intimate cooperation if real progress toward the ultimate goal of materials research — "molecular engineering" — is expected.

Success of the measurements man (usually an experimental physicist or physical chemist) depends upon his cleverness in "asking the right questions" in his experiment and upon having sensitive enough equipment to "hear nature's answer" unambiguously through the background noise. The theorist (usually a theoretical physicist or applied mathematician), tries to find a "theoretical model" to explain as many of the measured results and curves as possible. To check his "model", he advises the synthesis man what materials to make and the measurements man what crucial experiments to take on these materials.

In all three approaches, the materials scientist depends upon sophisticated apparatus. Most often he is no better than his equipment. Materials synthesis is based upon speck-pure chemical laboratories, facilities for high-temperature synthesis such as image-arc, flame-fusion, arc-melt, electron-bombardment and induction furnaces, and high-pressure facilities such as those needed, for example, for hydrothermal synthesis.

Similarly, modern equipment must be available for sophisticated measurements. Examples are magnets with very uniform fields over large areas, spin and nuclear magnetic resonance apparatus, sensitive susceptibility measuring equipment, and spectrometers for all spectral ranges.

The theoretical approach, finally, depends upon pencil and computing facilities, usually high-speed digital computers; occasionally analog equipment, including the electrolytic tank, is still used. In contrast to the other two approaches, failure in the theoretical approach can seldom be blamed upon the equipment!

6. Organization of Materials Research

The scientist who is able to work on all three approaches of materials research is a rare individual indeed. This is the reason why materials research is most successfully carried out by teams of scientists of different professions and talents who *together* cover the three approaches—synthesis, measurement and theory. Fig. 1 shows the essential elements of a typical materials research organization at RCA Laboratories. Although materials research may be organized somewhat differently in various laboratories, its main elements remain the same.

The materials research team, pictured in the center, usually consists at least of a synthesis and a measurements man. Some teams have their own theorist. Each major materials research project, such as photoconductor or phosphor research, is based upon such a team of scientists who literally pool their talents in the search for the common goal.

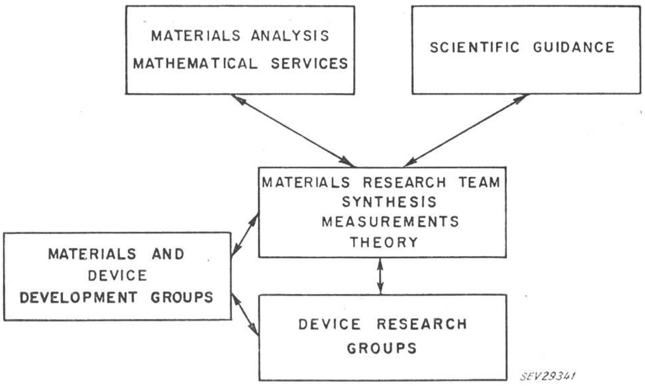

Fig. 1

Organization of Materials Research

The materials research team cooperates closely with groups which can provide the analytical services and scientific guidance on the one hand, and with groups which can assist in materials development and sampling. The main customer of all materials efforts are the respective device research groups

Even this team usually is not self-sufficient but depends upon the cooperation of other groups and individuals who provide services and advice. The "Materials Analysis" group specializes in the determination of the elemental components, impurity traces and atomic structure of a material. Physical analytic methods, such as X-ray, ultraviolet, light and infrared spectroscopy, electron microscopy and mass-spectrometric studies are used for this purpose and are complemented in part by very sophisticated, wet chemical analysis methods. Radio-isotopes are employed for super-sensitive trace-element studies. A research reactor, if available, can be useful for analysis by neutron activation and diffraction. "Mathematical Services" refers to programming and high-speed computing services, vitally important for basic materials research. While large research institutions usually have their own analytic and mathematical services, smaller laboratories often buy such services or rent facilities.

Of great significance for a successful materials research activity is the general scientific stimulation and guidance provided by a few outstanding scientists with international reputation in their fields. These experts may be members of a particular materials team, or they may be "scientific consultants" permanently or temporarily attached to the respective research activity. It goes without saying that these experts are the more valuable the higher they stay on top of their respective scientific fields. They obviously must select and direct their work accordingly. Small companies often depend entirely upon outside consultants, who usually are university professors, as their scientific advisers. For a large laboratory there are great advantages in having leading scientists located permanently in the laboratory and available whenever a problem arises. They provide an ever present critical advisory and sounding board for problems and novel ideas. They may save a company from initiating research on an idea which can be shown to be as inherently doomed to failure as the quest for perpetual motion. Less tangible in its direct economic effect is the definite contribution of these top scientists to the stature of a laboratory in the scientific world. They open the doors to other institutions. They often hear about scientific news before it appears in print and may thereby give the materials research a decisive lead in this rapidly changing field.

The "Materials and Device Development Groups" assist the materials research team to keep the device researcher happy by duplicating achieved results in new materials synthesis and providing him with large enough samples for his research.

7. Materials Classification and Some Conclusions

The variety of materials studied at an electronics research laboratory may be enormous. A classification can be arrived at in many different ways. In Table I the order is according

A. Classification of Materials

Table I

Energy Band Gap	Conductivity (in darkness)	Materials: without spontaneous polarization	Materials: with spontaneous polarization
High	Negligible	Dielectrics (Insulators)	Ferro-electrics
		Phosphors	
		Photoconductors (visible)	
	Low	Paramagnetic Materials	Ferrites
		Electron Emitters	
		Photoconductors (infrared)	
		Semiconductors	
Low		Thermoelectrics	
Zero	High	Metals	Metallic Ferro-magnetics
Zero	Infinite	Superconductors	

to the energy band-gap of the material. It is inversely related to the conductivity as indicated. The conductivity scale also seems to give an approximate indication of the degree of the existing physical knowledge on any of these materials and the related phenomena. This is a rather astonishing fact considering that some of the earliest known and most extensively studied materials head the list, such as insulating and luminescent materials, followed by photoconductors. Although scientific studies on luminescence go back to the 16th century, the basic complex mechanisms involved are still very much less understood than is semiconductivity, a relatively recent addition to the list of observed materials phenomena.

The reason for this peculiar situation lies in nature itself. It has been said that every additional electron volt of energy gap increases by at least an order of magnitude the difficulty to synthesize a crystal of equal chemical and structural purity. Semiconductors are distributed near a 1 eV gap, visible photoconductors around 2 eV, phosphors group around 3 eV, and their order of complexity increases accordingly. In addition, the difficulties for the synthesis chemist or metallurgist further grow when he progresses from elemental crystals, such as germanium or selenium, to binary compounds, such as indium phosphide or cadmium selenide, to ternary compounds. Solid-state theory at present is barely able to explain adequately "from first principles" the phenomena found in highest purity column IV crystals, Ge and Si. This standard of purity requires the content of foreign atoms to be less than one in a billion atoms, and the content of structural defects, exemplified by the dislocation density, to be below 100/cm^2. Progress toward better understanding of materials, therefore, is closely linked to the availability of chemically and structurally purer materials.

8. Recent Advances in Materials Research

Finally, the proposition that materials research has become a key factor in the progress of electronics can be illustrated by pointing to a few striking recent advances in materials. These advances can be expected to affect various areas of electronics in the near future. They must serve as representative examples, since completeness is obviously impossible here.

Major advances were recently made in improving photoconductors. These are materials which become conducting upon illumination by light. They are the basic materials for photo-detectors and television pickup devices.

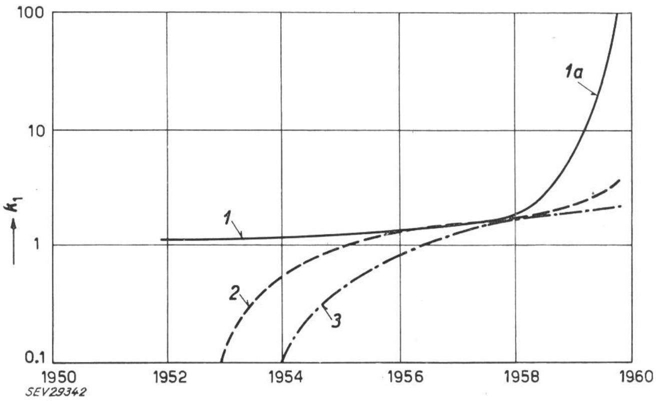

Fig. 2

Progress in Photoconductor Performance

After only nominal progress in photoconductor performance during the two preceding years, a breakthrough has recently been achieved in crystals. The reproductibility of the best fast crystals, however, is still small (about 25 %)

k_1 Performance factor; *1* Crystals; *1a* Fast Crystals; *2* Powders; *3* Sintered layers

Recently, large possible increases in performance were theoretically predicted for photoconductors with the correct impurity content[6]). During the past year, crystals were synthesized with about two orders of magnitude higher performance factors than ever known before, as shown in Fig. 2. Though an exceedingly difficult task, it can be assumed that eventually the same performance may be achieved in powders and sintered layers which are required for most photoelectronic devices. Infrared sensitive photoconductors have been perfected to a similar degree during the past few years. Their spectral response can now be tailor-made to an amazing degree.

[6]) See, for example: Review of Advances in Luminescence, Photoconductivity and Space-Charge Current Flow. RCA Rev., Vol. 20 (1959), No. 4, p. 529–784.

The phenomenon of space-charge-current flow[6]), well known in vacuum tubes, was recently predicted and later measured in highly purified insulators, such as cadmium sulfide. Initially considered no more than a particular aspect of photoconduction, space-charge current flow has recently for the first time been used in a solid-state analog to the vacuum-tube triode. Although still very much in its infancy, this high input-impedance amplifier device may herald a new class of "insulator devices" to reach importance as solid-state complements to the low-impedance semiconductor devices.

In all communications systems, signal amplification remains the pre-eminent function. Semiconductors today provide the basis for the most important solid-state amplifier devices for any frequency from audio up to microwaves. After an extensive search, gallium arsenide was selected as the semiconductor material with the best combination of advantages as mentioned before[7]). Its high carrier mobilities and high-temperature operating capability (up to 475 °C) place it potentially far ahead of germanium or silicon. A large effort is presently being aimed at purifying and controlled doping of gallium arsenide in several research laboratories. Last year, the first operating GaAs transistor was demonstrated, a major event in this field. Parametric and tunnel diodes will soon find their way into television sets. GaAs diodes of both types have a higher frequency response and lower noise factor than any similar device made of germanium or silicon. As mentioned before, the last word on the "ultimate" semiconductor has not been spoken yet. Search for better ternary (or three-element) compounds has led to two materials with very promising properties for tunnel diode and thermoelectric applications. Still better ones may be uncovered.

Information storage, such as used for video recording or digital computers, is being achieved in ever tinier specks of ferromagnetic and other materials. From magnetic cores, printed ferrite and metal plates with microscopic holes, the need for higher information-storage density leads to magnetic tapes and films. Further improvements in ferroelectrics may ultimately make them practical for certain switching and storage functions. Basic studies carried out on new superconductors and on the mechanism of switching will permit improving the design of novel cryogenic memory and storage devices.

Finally, materials research is of primary importance for electronic power "generation". Electronic conversion of radiation into electricity, without use of moving mechanical parts, opens many new possibilities. Photovoltaic, thermionic and thermoelectric principles are most promising and mutually complementary in their operating temperature ranges and fields of application. All three methods depend critically upon new materials for success.

The best silicon photovoltaic cells, such as used for secondary power supplies in satellites, now convert up to 13 % of the available solar energy. Much research work is presently being carried out to increase this efficiency by means of better materials. Novel refractory alloys are being developed to improve the critical part of thermionic converter tubes, the high-temperature electron emitter. Thermionic converter tubes operating at a cathode temperature of about 2600 °C and an anode temperature of over 1000 °C, have achieved an energy conversion efficiency of about 10 %. Materials advances can be expected to improve this efficiency. Thermo-couples, complementing thermionic converters, are best suited to operate at temperatures below 1000 °C. Recent thermoelectric materials research has led to new and very promising semiconductor alloys. With thermo-elements operating at a temperature drop of only 300 °C down to room temperature, energy-conversion efficiences of as high as 7 % have been measured. Materials developed for the range up to 1000 °C promise to more than double this efficiency. Although at present still less efficient than mechanical heat engines, thermionic and thermoelectric power converters have already proved valuable for special applications and, depending upon advances in materials, may eventually become a major factor in primary energy generation.

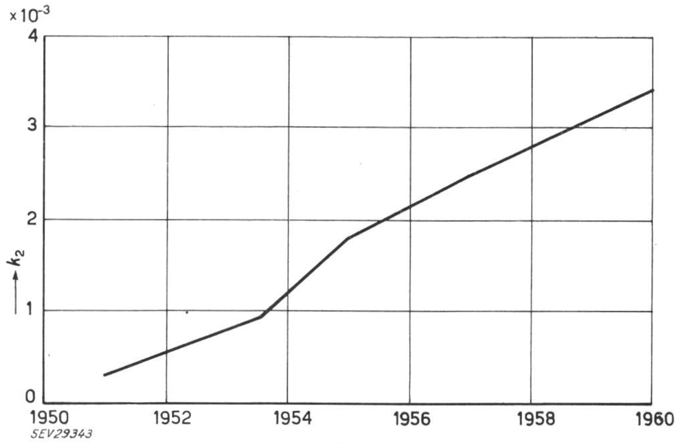

Fig. 3

Progress on the Cooling Efficiency of Thermoelectrics

The cooling efficiency of a thermoelectric material is generally expressed by a figure of merit. Assumed is that the hot terminal of the thermocouple is at room temperature. Progress over the past few years is shown. Using materials with a figure of merit of 3×10^{-3}, a thermoelectric refrigerator can be built to operate about as efficient as a small or about half as efficient as a large, commercial mechanical refrigerator k_2 Figure of merit

The temperature range of operation of a thermoelectric material is one of the main factors determining its best composition. Materials for thermoelectric cooling below room temperature therefore are quite different in composition from those designed for power generation. Advances made during the past decade are shown in Fig. 3. The cooling efficiency of a refrigerator based upon a material with a figure-of-merit of 3×10^{-3} is about equal to that of a small, or about half the efficiency of a large, commercial refrigerator. Considerable materials improvements are theoretically possible and can be expected. They will be followed by an expansion of applications from the special — such as electrically cooled infrared detectors — to, ultimately, general room cooling.

9. Conclusion

Materials research has recently acquired a pre-eminent position in electronics. The demands for new and better

[7]) See for example *D. A. Jenny:* The Status of Transistor Research in Compound Semiconductors. Proc. IRE, Vol. 46 (1958), No. 6, p. 959–968.

materials increase rapidly. The complexity and sophistication of materials research are growing. Teams of scientists with the required diverse talents handle the three-fold aspects of materials research. True "molecular engineering", the ultimate goal of materials research, lies still far in the future. Much more knowledge has to be accumulated on the basic properties of matter before engineering on the molecular level will be possible. Long-range fundamental investigations are expected to produce the required new insight and thereby provide broad scientific guidance in today's accelerated search for improved materials.

The present explosive expansion of electronics will continue into the future, gradually affecting all branches of technology. The dependence on materials advances will grow further, and materials research will rapidly become the key to progress in electronics.

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Das Betriebsübertragungsmass eines allgemeinen linearen Vierpols

Eine didaktische Studie

Von *H. Weber,* Zürich

621.372.5

Im allgemeinen wird das Betriebsübertragungsmass als zweckmässige Grösse für das Betriebsverhalten eines Vierpols zwischen Quelle und Verbraucher behandelt und seiner Definition gemäss aus den Vierpolkonstanten und den Abschlussimpedanzen berechnet. Damit verliert diese Grösse ihre Anschaulichkeit. Erst mit der Darstellung aus den Wellenparametern des Vierpols und den Abschlussimpedanzen gewinnt das Betriebsübertragungsmass wieder etwas Vorstellbares. Man kann aber, wie das im folgenden gezeigt wird, das Betriebsübertragungsmass direkt aus den Wellenvorgängen auf verallgemeinerten Leitungen herleiten. Dazu benötigt man nur die Kenntnis der Vorgänge an der Stossstelle zweier Leitungen mit verschiedener Wellenimpedanz und die Beschreibung eines Vierpols durch seine Wellenparameter. Sinngemäss lässt sich diese Vorstellung auch auf die Mikrowellenvierpole anwenden. Die Betriebs- und Echoübertragungsmasse erhalten damit eine enge Beziehung zur Streumatrix.

1. Vorgänge an einer Stoßstelle (Fig. 1) für eine andauernde Sinusschwingung mit der Kreisfrequenz ω:

Einfallende Welle: U_1, I_1,

Scheinleistung: $S_1 = U_1 I_1; \quad \dfrac{U_1}{I_1} = Z_1$

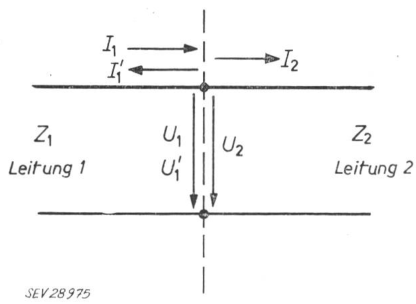

Fig. 1

Kettenschaltung zweier Leitungen, Stoßstelle

U_1, I_1 Einfallende Welle
U_2, I_2 durchlaufende Welle
U_1', I_1' reflektierte Welle
Z_1, Z_2 Wellenimpedanzen

Durchlaufende Welle: U_1, I_2,

Scheinleistung: $S_2 = U_2 I_2; \quad \dfrac{U_2}{I_2} = Z_2$

Reflektierte Welle: U_1', I_1',

Scheinleistung: $S_1' = U_1' I_1'; \quad \dfrac{U_1'}{I_1'} = Z_1$

Es gelten folgende Zusammenhänge:

$$\begin{matrix} U_2 = d_u U_1 \\ I_2 = d_i I_1 \end{matrix}; \quad S_2 = d_s S_1 \qquad d_s = d_u d_i \tag{1}$$

$$\begin{matrix} U_1' = r U_1 \\ I_1' = r I_1 \end{matrix} \quad S_1' = r^2 S_1 \tag{2}$$

Reflexionskoeffizient r:

$$r_u = r_i = r$$

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{3}$$

Durchlasskoeffizient d:

$$d_u = 1 + r, \; d_i = 1 - r$$

$$d_s = 1 - r^2 = \frac{4 Z_1 Z_2}{(Z_2 + Z_1)^2} \tag{4}$$

Wellenimpedanzen der Leitungen: Z_1, Z_2:

2. Vorgänge an einem zwischen zwei verschiedenen Leitungen eingeschalteten allgemeinen, linearen Vierpol. (Bezeichnungen siehe Fig. 2):

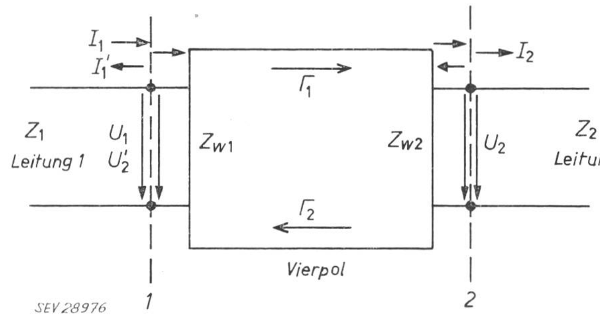

Fig. 2

Vierpol mit vorgegebenen Wellenparametern zwischen zwei Leitungen

Z_{w1}, Z_{w2} Wellenimpedanzen
Γ_1, Γ_2 Wellenübertragungsmasse
Weitere Bezeichnungen siehe Fig. 1

Würde an den Klemmenpaaren *1* und *2* Anpassung herrschen, d. h. $Z_1 = Z_{w1}$ und $Z_2 = Z_{w2}$, so würde für eine von *1* nach *2* laufende Leistungsübertragung gelten:

$$\frac{S_1}{S_2} = e^{2\Gamma_1} \quad \frac{U_1}{U_2} = \sqrt{\frac{Z_{w1}}{Z_{w2}}}\, e^{\Gamma_1} \quad \frac{I_1}{I_2} = \sqrt{\frac{Z_{w2}}{Z_{w1}}}\, e^{\Gamma_1} \tag{5}$$

Für eine von *2* nach *1* wirksame Leistungsübertragung dagegen: