Introduction

By R. A. HEISING

THE history of the quartz plate development as an essential and valuable element in the radio telephone involves a number of unusual phases which are not generally associated with important inventions. The piezoelectric property of quartz and other materials was discovered by Pierre and Jacques Curie in 1880. For over three decades this piezoelectric property was nothing more than a scientific curiosity. The peculiar properties of quartz and certain other materials formed the basis of classical researches during that period, and in 1910 a book was published by Voigt which included a treatment on the theory of piezoelectricity. It remained a scientific curiosity until World War I, when studies were begun on the piezoelectric properties of quartz and of Rochelle salt, and applications were made of them to devices for use in the war.

In 1917, inspired by the submarine problem of World War I, Professor Paul Langevin of France, and Mr. A. M. Nicolson, then in the Research Department of the Western Electric, independently initiated work on the utilization of piezoelectric devices for picking up compressional waves from the sea. Langevin developed an echo system employing supersonic waves, both the supersonic emitter and the supersonic pickup consisting of quartz plates. After the war his French Company equipped a number of vessels with depth sounding apparatus of this type. His United States patent 2,248,870, issued in 1941, is directed to that apparatus. Nicolson worked with both quartz and Rochelle salt. Finding that Rochelle salt responded very strongly to sound waves and to electric excitation, he commenced development of a series of devices including microphones, loud speakers, phonograph recorders and pickups. Some of these are described in the Transactions of the American Institute of Electrical Engineers for 1919, and many others in his numerous patents.

One of the sound pickup systems which Nicolson disclosed in his patent application of 1918 employed a piezoelectric crystal as the control element in a vacuum tube oscillator. Nicolson's patent directed to the oscillator issued in 1940 as United States patent 2,212,845.

About the end of World War I, Dr. Walter G. Cady of Wesleyan University took up the study of piezoelectricity and applied for patents on crystal controlled oscillators. His first patents were issued in 1923, and he presented papers[1] before engineering and scientific societies describing the per-

[1] "The Piezoelectric Resonator," W. G. Cady, *Proc. I. R. E.*, Vol. 10, 1922, pp. 83–114.

formance of quartz resonators and of oscillators in which such resonators controlled the frequency. He explained to the scientific and engineering world the superior frequency stability of the quartz controlled oscillator, and he suggested the possibilities of using a quartz resonator for precision frequency measurement or standardization. He pointed out that the quartz controlled oscillator possessed a stability that was far better than that attained by the electrical oscillators of that time. Cady showed how quartz crystal elements could be attached to electric oscillators and could exert a stabilization control in spite of variations in the resonant frequency of the electric circuit that were liable to occur with temperature, vibration and normal inaccuracies in adjustment.

Cady's circuits differed from Nicolson's in one or more respects. Most of Cady's circuits consisted of an electric oscillator to which the crystal was attached so as to influence the reactance of the oscillatory circuit, or connected so as to influence the feedback from the tube's output circuit to its input circuit. One of his circuits utilized the crystal as the resonating element with a multistage amplifier but without any electric resonant circuits. Nicolson's circuit using Rochelle salt crystals contained no electrical circuits for controlling the frequency without the crystal, and it operated with a single vacuum tube.

Some time after Cady's publication, Prof. G. W. Pierce, of Harvard devised a number of circuits. Pierce showed that it was possible to do with quartz what Nicolson had been able to do with Rochelle salt, that is, construct oscillators with a piezoelectric element and a single electron tube but without the electrical resonant circuits which were used by Cady.

Just as a lapse of time occurred between the discovery of piezoelectricity and its first developments, another lapse occurred between the invention of the crystal oscillator and the discovery of its principal application. The fields of use contemplated at first appear to have been frequency standards and measurements. The Bureau of Standards became interested, as it was the logical organization to maintain the highest of standards of measuring devices and frequency falls into the class of those things for which it should maintain standards. Cady during this period carried out a number of comparative measurements between standards in this country and in Europe.

To show how the crystal found its present major field of use it is necessary, however, to go back eight or ten years and pick up the threads of a paralleling art and follow its progress and its difficulties until it reached the stage where it engulfed the crystal.

The development in 1913 and 1914 of the high-vacuum, three-electrode amplifying vacuum tube as a telephone repeater provided the basic element for the radio telephone. In 1914 the Bell research engineers in the Western Electric Company, after putting the vacuum tube onto telephone lines so that the continent was spanned for the first time by a wire telephone circuit, began active work on a radio telephone. In 1915 they established experimentally a one-way radio telephone whereby speech was transmitted across oceans for the first time, and signals from Arlington, Virginia, were received at Paris, France, Darien in the Canal Zone, and Pearl Harbor.

When World War I began, the background and experience of this work were placed at the service of the government, and the first practical radio telephones ever made were developed. A radio telephone transmitter circuit employing plate modulation had been devised which was sufficiently simple to adjust and suitably easy to operate so that it could be put into the hands of military people for war purposes. This transmitter and a radio receiver, which for some time had been standard for telegraph reception but to which was added a speech amplifier, constituted the first two-way radio telephone equipment. In 1918, submarine chasers, transports, and vessels of the U. S. Navy were equipped with this radio telephone. A microphone and loud speaker on the bridge provided for rapid communication between ships when submarines were sighted. Instant warning could be given from any ship in a convoy to all others merely by lifting the receiver off its hook and speaking, as with the military radio telephones of today. Practically every ship in the Navy was equipped with one of these sets, and the equipment, therefore, saw actual war service.

Corresponding sets developed for airplanes were used extensively in the United States during the spring and summer of that year, in training, in practicing formation flying, and in developing aircraft tactics in anticipation of the time when our planes and the equipment would arrive on the battlefront. The sets began arriving in Europe just before the Armistice in 1918. Although the airplane radio equipment did not give battle service, both the airplane and the naval radio equipments had a chance to demonstrate their worth and possibilities, and to prepare the way for developments which have appeared in this war.

After the war, broadcasting sprang up, based upon the technical developments that were used in the war, knowledge of which had become widely disseminated. Broadcasting developed rapidly and, in a few years, the country was dotted with transmitters and millions of people were listening with factory-made or home-made sets.

During these years, the crystal art and the radio art moved along side by side but with no connection beyond that provided by the utilization of crystals at the Bureau of Standards for standardizing frequencies and, in a few laboratories, for laboratory measurements. The frequencies of all radio transmitters were set by tuned circuits not differing greatly from those used in the experimental radio telephones of 1914 and 1915. No reason had been advanced to show any need for such an element as a crystal in a radio transmitter, and the ordinary electric oscillator had so many points of superiority over the crystal controlled oscillator, in power handling capacity, ease of adjustment, simplicity and cost, that no one even suggested using a crystal in the broadcast transmitters. Reasons justifying such use, however, were ultimately pointed out by others than the inventors of the various piezoeletric oscillators. The discovery of the need came about in its own peculiar way.

In these early days, the American Telephone and Telegraph Company operated the broadcasting station WEAF in New York. Occasionally complaints were received about terrible quality observed from the station. The telephone engineers had prided themselves on knowing how to produce high quality and on actually producing high quality from their radio transmitters. The cause of these unexpected complaints of bad quality was rather puzzling. Some listeners reported bad quality at the same times that other listeners reported excellent quality. Checking a few listeners' sets showed that the phenomenon was associated with location. At the home of one member of the telephone company near New Canaan, Connecticut, the quality of reception during evenings was atrocious. With this as a basis, engineers of the Research and Development Department of the American Telephone and Telegraph Company began a study as to the cause of this bad quality. These engineers, Messrs. R. Bown, R. K. Potter and D. K. Martin, published the results of their study in February 1926.[2] They found that during the day signals received at New Canaan, Connecticut, were good, but in the evening when signals could arrive not only by a direct path over the ground but by a reflected path from the ionized regions of the atmosphere, quality became bad. A series of tests disclosed what caused this trouble. Radio transmitters up to that time had consisted of an oscillator that was plate modulated, and the frequency of the oscillator would vary a few cycles during cyclical modulation by each and every tone. The radio signals arriving at New Canaan by two paths that differed in length possessed different momentary frequencies because of the variable frequency of the transmitter and of the different times required to reach New Canaan over the two paths. The momentary differences in frequency produced interference in the resultant radio wave as picked up by the receiving antenna and gave a badly distorted signal, sometimes unrecognizable in character.

The engineers were able to show that by using a very constant frequency control on the transmitter which prevented any variation during the modulation cycle, the quality was very much improved. In order to provide this constant frequency control during modulation they utilized a quartz cyrstal oscillator with amplifiers to drive the power tubes.[3] WEAF, therefore, to

[2] "Some Studies in Radio Broadcast Transmission," Ralph Bown, DeLoss K. Martin and Ralph K. Potter, *Proc. I. R. E.*, Vol. 14, 1926, pp. 57–131.

[3] First applied about June, 1924.

which this scheme was applied became the first crystal-controlled broadcasting station and became the first station which surmounted the bad quality produced by the phenomenon of reflection from the ionized layers. It demonstrated to radio engineers the necessity for better frequency control than had been considered necessary up to that date. Thus the crystal oscillators of Nicolson, Cady and Pierce were suddenly given wider use, and new values were placed upon them in the field of radio communication.

With the quartz plate and the crystal oscillator suddenly taking on greater importance in improving quality, the problem of frequency stability as needed in radio was only half solved. The present systems of radio communication could not be carried on with the quartz plates and the circuits of the date mentioned—1926—or even of 1930. Aircraft communication, for instance, with crystal oscillators was only made possible by means of further inventions and developments.

During the late twenties and early thirties, air transportation increased by leaps and bounds in the United States. The matter of safety in air travel became of utmost importance from the viewpoint of the public. Weather changes in the form of sudden development of cloudy and other hampering atmospheric conditions about a destination airport often left a transport airplane helpless as to where to go. Many planes crashed before they could locate a landing field. Radio telephone communication from airports to planes solved that problem. Planes could be informed before arrival as to conditions, and could locate also a clear airport at which they could land. However, the airplane sets at first had to be electric oscillators with all their variabilities. It was not feasible to use in airplanes crystals that performed very satisfactorily at ground stations because the vibration of the airplane jiggled the crystals in their holders and prevented their operating.

This problem was solved by the invention of a radically new method of holding the crystal. Mr. G. M. Thurston of Bell Telephone Laboratories discovered that corners and edges of crystals were partially and sometimes wholly quiescent, and that by clamping the crystals suitably, they could be used in vibratory locations. The airplane radio problem of the greatest magnitude was thereby solved, and the way paved for the modern airplane set.

In the meantime other things were giving trouble. The crystal oscillator was still subject to temperature variations. Interference between broadcasting stations, even though hundreds of miles apart appeared in the form of beat notes, and gave trouble if of 50 cycles or more. The constancy of the frequency of a broadcasting station with early crystals was insufficient to eliminate this trouble unless precise temperature control equipment was used with the crystal. In an airplane that rises in a summer day sometimes into winter temperatures, temperature variation could shift the frequency out of the channel. The use of temperature control equipment was very necessary on planes but was costly, bulky and troublesome.

Mr. W. A. Marrison[4] of the Bell Telephone Laboratories, who had been working since 1924 for an extreme precision of crystal oscillators, found by 1927 that a quartz crystal with a low or zero temperature coefficient could be made. He made his crystal in the shape of a doughnut from a slab cut parallel to the natural side face. The doughnut crystal was impractical for general commercial uses, but it demonstrated that by properly utilizing the properties of quartz a low coefficient could be obtained. The Bell Telephone Laboratories radio research division which had been continually expanding its work on crystals, turned its efforts in this direction. As a result, there were discovered and developed the low temperature coefficient quartz crystals known as the AT and BT cuts. These were described by the inventors, Messrs. F. R. Lack, G. W. Willard, and I. E. Fair of the Bell Telephone Laboratories in a paper published in the *Bell System Technical Journal* in 1934.[5] With this invention and development, the crystal no longer needed any temperature control for most uses, or only a very simple one for the most exacting conditions.

With this discovery of favorable orientations and dimensions for simply shaped crystal bodies with low temperature coefficients the way was opened for further advances. There followed the work on the CT and DT cuts by G. W. Willard,[6] the ET and FT by S. C. Hight, and then the GT by W. P. Mason,[7] all of the Bell Telephone Laboratories. The GT crystal was and is the crystal with the flattest temperature-frequency curve so far developed. A clock controlled by one such crystal has surpassed in precise time recording all the clocks usual for such purposes. Other low temperature coefficient cuts have since been developed, the latest described in 1944 in the technical press is considered later in this book.

With initiation of military preparedness in this country, another type of problem arose. The military forces were going to need a large number of radio transmitters. Every battleship, cruiser, destroyer, motor boat or submarine would require one or more radio telephones; and the Navy was to be expanded. Every airplane and tank in the Army also would require radio telephones; and there were to be tens of thousands of these vehicles. Every landing field would need to be equipped. Every regiment, and per-

[4] "A High Precision Standard of Frequency," W. A. Marrison. *Proc. I. R. E.*, Vol. 17, 1929, pp. 1103–1122.

[5] "Some Improvements in Quartz Crystal Circuit Elements," F. R. Lack, G. W. Willard and I. E. Fair, *B. S. T. J.*, Vol. 13, 1934, pp. 453–463.

[6] "A Simplified Circuit for Frequency Substandards Employing a New Type of Low Frequency Zero Temperature Quartz Crystal," S. C. Hight and G. W. Willard, *Proc. I. R. E.*, Vol. 25, 1937, pp. 549–563.

[7] "A New Quartz Crystal Plate, Designated the GT, Which Produces a Very Constant Frequency Over a Wide Temperature Range," W. P. Mason, *Proc. I. R. E.*, Vol. 28, 1940, pp. 220–223.

haps many smaller units would need radio equipment. Artillery would use them in spotting. They would be required for connection to headquarters. The enemy would also equip their forces similarly, and the ether would be jammed full of radio communications.

In peace uses a geographical separation of different channels assists in preventing interference; but in war, all branches of the military services—even including the Navy—would be operating in the same neighborhood and it would be necessary to set up all the channels without benefit of any geographical separation. Since many channels were going to be required they had to be placed closer together, and the frequencies utilized had to reach further into the high frequency region. Nothing but crystal control would place the frequencies accurately enough and maintain them there, especially in airplanes, tanks, and portable radios. Whereas in peace time a radio set usually operates on one frequency only, requiring only one crystal for transmitter control, in war each set might be called upon to operate upon any one of a dozen different frequencies, or fifty, or even one hundred and twenty. A crystal would be necessary for each frequency in the transmitter.

In addition, although one may operate a radio receiver without any crystal, the broadcast transmitter alone using a crystal, such receiver tuning cannot be depended upon in military communication. To secure channel separation the beating oscillator in the receiver must be as steady as the transmitter frequency. The receiver tuning must be instantly adjustable permitting immediate communication, as one cannot expect a busy transmitter operator at the battle front to talk for a testing period while the receiver is being tuned. These requirements meant crystals in receivers just as well as transmitters. The demand for crystals for military purposes therefore simply skyrocketed beyond any peace time demand ever conceived. The Western Electric Company alone, in its several plants, for several years has manufactured more crystals per day than it used to make per year in its regular crystal factory. Scores of other crystal factories were started up to supply the demand; and problems of manufacture then came to the fore.

In the continued research and concentrated development work of the Bell Laboratories upon quartz crystals, there naturally came about during the previous years developments in machines, processes, and instruments for the manufacture of the crystal plates suitable for commercial and governmental uses. These processes after development in the laboratory were instituted by the Western Electric Company in its factories where they were further developed and improved. The problems of holders, for example, and also the interference by spurious vibrations in plates had long been subjects of intensive investigations. In the Bell Telephone Laboratories the staff of engineers and physicists giving full time to these and other problems of quartz crystals had grown to be the largest in the world. The Western Electric Company meanwhile had become one of the largest manufacturers of quartz plates, and at the time war started was the only one which could make certain designs that would insure the highest standards of performance.

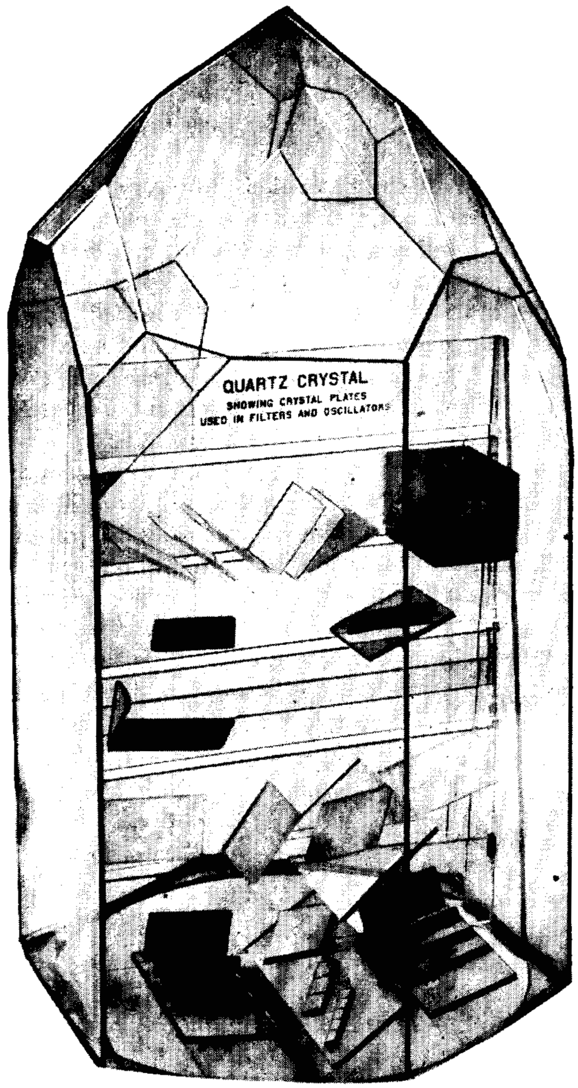
It was only natural, therefore, when preparedness activities began, that the government, which was interested in crystals of the highest quality, should look to the Western Electric for assistance in the expansion of the crystal manufacturing facilities of the country. With the thousand-fold expansion in crystal manufacturing facilities that was necessary and the decentralization that is wise from the military standpoint, scores of manufacturers had to be educated in the art and science of crystal manufacture. The Western Electric Company made its technical and manufacturing art available to the Signal Corps, and through it and in cooperation with it to crystal manufacturers throughout the nation. The Bell Telephone Laboratories as the research and design associate of the Western Electric placed all its most confidential information on crystals at the disposal of the Government. Memoranda from its files and laboratory reports were made available, as well as manufacturing processes and procedure.

The Western Electric Company in meeting its orders found it necessary to expand its crystal production 750-fold. To accomplish this it was necessary to introduce to the intricacies of crystal manufacture a large number of engineers inexperienced in that art. The members of the Bell Laboratories technical staff who carried out the early studies and developments prepared a series of lectures to assist these newcomers, both those in its affiliated organization and those in the several companies which the Signal Corps wished educated. These lectures were mimeographed and widely disseminated. The demand for the lectures has exhausted the supply. It appears desirable, rather than to remimeograph, to place a somewhat revised version of the lectures in permanent form. Hence they are presented herewith in book form.

Although the early use of quartz crystals and the major demand for them in this war are for frequency control in oscillators, that is not the only field of use. The crystal plate, as a vibrating element, should find use in any field in which a tuned circuit is employed. This is especially true for "electric wave filters." These selective circuits have already found wide use in the telephone plant; and their requirements, although lagging in quantity behind that of radio oscillators, have been climbing rapidly. Crystal filters have facilitated materially the development of the coaxial cable with its hundreds of channels over one circuit. At the time of the entry of this country into the war, the use of crystal filters in the telephone plant was growing so that the rate of manufacture of quartz plates for the filters was about the same as for radio oscillators. Although crystal filters have been embodied in military equipment, their number is relatively small as compared to radio oscillators. With the termination of the war, however, it is expected that relative uses may revert to approximately the prewar relationship. In fact, in view of coaxial line developments, the field for telephone use is such that there is every reason to believe the number of filter crystals made annually may even exceed the number made for oscillators. This prospective use more than justifies the inclusion in this book of some material on crystals for filters.

The decision to publish the material of this volume has presented its own problem. All the engineers involved are deeply engaged in war work and it was impractical to gather and arrange the material in the logical treatise form that might be preferred. A number of the lectures in revised form have already appeared in the *Bell System Technical Journal*. The other lectures have, therefore, been revised as their various authors have been able to find time. With this introduction they are all assembled under one cover. Included also is an article on a new low coefficient cut of crystal that was published in April, 1944.

A book assembled in this manner cannot be quite as thorough or consistent as one planned and written by a single person. There will be duplication to some extent, especially when the duplication makes the work of each contributor easier. There will at times even be contradictions since various pieces of work were done at different times by the different contributors, and their lectures likewise prepared at different times. However, whatever shortcomings there are, it is hoped they will give little trouble. The material despite its manner of accumulation should fill a gap in the literature and represent in part at least the contribution to the art which its authors would wish it to be.



Model of a Quartz Crystal having within it a number of low temperature coefficient quartz plates placed in the regular positions at which they are cut