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INTERACTION OF ELECTRONIC CURRENT WITH HYPERSONIC WAVES IN SOLIDS

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Summary

The possible device applications of ultrasonic amplification in piezoelectric semiconductors, particularly at ultra-high and microwave frequencies, are discussed. Power output, noise level, and efficiency are considered and the present situation in the construction of transducers for extracting r.f. power is surveyed. The phenomenon of current saturation in cadmium sulphide, which is thought to be a related effect, is also discussed.

Author

I. Introduction

The interaction between an electron current and acoustic waves in a piezoelectric semiconductor (CdS) was first described by White(1) and his co-workers. Their analysis(2) was of a form familiar to workers in the microwave tube field, and Dransfeld(4) gave a qualitative explanation of the effect in traveling-wave-tube terms. It was said that the electrons drifting through the semiconductor were bunched by the electric field due to the acoustic wave. If the drift velocity of the electrons is slightly greater than the acoustic wave velocity, then the bunches move forward into a region of decelerating electric field, thereby giving up their energy to the field. Quate(6) pursued the analogy further and set up the equations in the coupled-mode formulation.

At about the same time, Smith(3) discovered a current saturation effect in Cadmium Sulphide. Saturation began as the drift velocity of the electrons approached the acoustic wave velocity. Rose(3) offered the explanation that under these conditions strong acoustic oscillations would be set up, and the electrons would be "trapped" in the troughs of the associated electric wave. This theory has since been criticised(5), and we discuss the phenomenon in more detail below.

One of the consistent difficulties encountered in this work, particularly at high frequencies, has been the fabrication of efficient transducers for the excitation of the ultrasonic waves. The results so far achieved are given below.

II. Gain, Power Output, and Noise

The theory developed by White(2) leads one to expect very considerable gains per centimetre of crystal length and, in fact, figures of 150 db/cm. have been found. On the other hand, the actual overall gains of practical devices have been of the order of only 40 to 50 db. The basic reason for this is that the maximum output power is low and is not very far above the noise level. We give some simplified calculations below which provide estimates of the performance which may be expected from the acoustic-wave amplifier.

The d.c. energy which is converted into r.f. power in a traveling-wave tube is the kinetic energy of the drifting electrons. An electron moving with the velocity of sound in Cadmium Sulphide has a velocity of about 5×10^3 metres/sec. This corresponds to an energy of about 70×10^{-6} electron volts. Consequently, for every ampere of d.c. current we have only 70 microwatts of available power for conversion into r.f. Given reasonable efficiency, this implies saturated power output levels of the order of 10 microwatts.

The noise power in the acoustic waves in the crystal comes from two sources. There is the contribution $kT\Delta f$ from the acoustic modes themselves, and also that induced by the current. The latter can be estimated as follows:

If the electromechanical coupling is small:

$$J \doteq -j\omega\epsilon E$$

$$\therefore \quad \frac{\epsilon EE^*}{2} = \frac{JJ^*}{2\omega^2\epsilon} .$$

By definition,

$$K^2 = \text{Electromechanical Coupling Constant}$$

$$\doteq \frac{\text{Mechanical Energy Density}}{\text{Electrical Energy Density.}}$$

$$\therefore \quad \text{Electrical Power} \doteq \frac{1}{K^2} \times \text{Associated Mechanical Power.}$$

$$\therefore \quad P_n = \text{Mechanical Noise Power}$$

$$= K^2 \frac{\epsilon EE^*}{2} v_s A = \frac{K^2}{2\omega^2\epsilon} /J/^2 v_s A$$

where v_s = velocity of propagation

A = cross-sectional area.

If we assume full shot noise, then $/J/^2 = \dfrac{2eI\Delta f}{A}$

where I = dc current density

e = electronic charge.

$$\therefore \quad P_n = \frac{K^2 v_s}{\omega^2\epsilon} eI\Delta f .$$

As is shown in White's paper$^{(2)}$, the frequency of maximum gain is given by

$$\omega^2 = \frac{ev_s^2\sigma}{kT\mu} .$$

We also have that

$$I = \sigma E$$

$$v_s = v_D = \mu E,$$

where v_D = Electron Drift Velocity. Inserting these values, we obtain:

$$P_n = K^2 \, kT\Delta f.$$

That a calculation of a shot-noise effect should give us a result apparently connected to resistor noise is, at first sight, surprising. However, we should remember that the semiconductor is in fact a resistor, and that K^2 represents the strength of the coupling between two transmission systems, one electrical, the other mechanical. In both of these the basic noise spectrum is given by $kT\Delta f$.

Thus the effective noise power at the input to an acoustic amplifier is of the order of $kT\Delta f$, if we neglect the other types of semiconductor noise.

At room temperature, with a noise bandwidth of 100 Mc/s, this represents 4×10^{-7} microwatts, and thus for a 1 kMc/sec. amplifier, one cannot expect the maximum output power to be more than about 70 db above the input noise level. This does not include all possible sources of noise, and may be an over-optimistic figure. Transducers for U.H.F. at present have insertion losses of over 10 db and consequently overall gains will be less than 50 db.

Another important quantity is the joule heat loss in the crystal. At 1 kMc/sec. this will be about 300 watts per cubic centimetre. These losses will increase with the square of the frequency, and it may be that this more than any other difficulty will prevent useful operation at higher frequencies.

III. Transducers

During the development of the acoustic amplifier, three types of transducers have been used. Chronologically, these are:

(a) A layer of quartz bonded onto the CdS crystal.

(b) A high-resistance layer in the crystal itself obtained by diffusing impurities into it(7).

(c) Thin-films of Cadmium Sulphide deposited on a substrate and subsequently heat-treated to increase their resistivity(8,9).

The first type is suitable only for low frequencies because of difficulties of construction and losses at the bond between the quartz and the crystal.

The second type eliminates the bond, but the uniformity of the diffusion layer seems to be the limiting factor. Little attention has been devoted to improving this(8), and the third type of transducer seems to be superceding it at high frequencies.

Thin-film techniques with Cadmium Sulphide have been developed for other applications, and it was natural that they should be applied to this problem. When deposited, the crystals have their axes aligned in the most suitable direction, but the heat-treatment is found to spoil the alignment somewhat.

Quate(9) has attempted to use successive thin-films of differing properties to obtain an improved match between the acoustic and electromagnetic waves. The principle is that of the quarter-wave transformers used for radio-frequencies. With such devices, decrease in the insertion loss has to be traded for decrease in bandwidth, but Quate's results of 10 db loss at 600 Mc/s. are the best so far achieved.

IV. Oscillations and Instabilities

The Cadmium Sulphide amplifier with its high gain, and considerable reflections from the output transducers, might be expected to be unstable and this is found to be the case. The nature of the oscillations is not certain however. This may be seen from the following consideration.

Any non-equilibrium distribution of space-charge in the crystal will return to a stable configuration as fast as the electrons are able to move. Similarly any mechanical strain in the crystal will tend to remove itself by movements which will propagate with the sound velocity. Consequently, the condition that v_D equal v_s is appropriate for coupling between <u>any</u> mechanical disturbance and the electrons. Further, if the electrons are to be slowed down and contribute energy to the disturbance, then v_D must be slightly greater than v_s.

In general then, when conditions are correct for interaction in the manner described by White, they are also ripe for <u>any</u> interaction between field and electrons. One must not attribute all the observed effects to this traveling-wave mechanism without more justification.

Two types of oscillations in Cadmium Sulphide have been observed, one coherent, and the other apparently incoherent.

The first was observed by R. W. Smith in this laboratory when investigating the non-ohmic behavior of Cadmium Sulphide. In general, the current through a crystal saturates when the electrons move with a drift velocity equal to the sound velocity. When the applied voltage was swept, oscillations were seen in the current through some crystals, with frequencies of two or three megacycles. The mechanism of these oscillations is still being investigated by Smith and others.

When a rectangular pulse with a fast rise time was applied to the crystals it was seen that initially the current reached its ohmic value and then decayed with a time constant of a few microseconds.

McFee(5) repeated this last experiment with an ultrasonic transducer attached to the crystal. He found that the decay of the current was associated with the build-up of ultrasonic flux in the crystal. The output from the transducer had the appearance of broad-band noise and, after some initial transients, seemed incoherent.

Rose(3) offered an hypothesis to explain the saturation effect which suggested that, as oscillations built up, the electrons became trapped in the troughs of the electric waves. No such behavior has been observed in traveling-wave tubes, and this explanation seems incompatible with the later observations by McFee. A strong trapping effect of this type would require, one would think, a strong single-frequency oscillation.

McFee suggests that the electrons are slowed down by their interaction with the ultrasonic waves in the manner described by White. Considered against the TWT however, the efficiency of the interaction seems remarkably high. The amount of the departure from ohmic behavior is a measure of the amount by which the electrons have been slowed down, and this can be quite considerable.

To summarize, the instabilities seen are not completely understood and, until they can be analysed and controlled, will be an embarrassment to any attempt to construct a useful ultrasonic amplifier.

V. Other Possible Devices

(i) Since the White amplifier is in some respects an analogue of the TWT, it is reasonable to seek the equivalent crossed-field device.

In crossed-field tubes, the source of r.f. energy is the potential gained by the electrons as they move from the sole to the circuit. If the anode voltage is V_A and the current is I_0, then the maximum available d.c. power is $V_A I_0$.

For a semiconductor, V_A will be the Hall-effect voltage and this is usually of the order of microvolts. Thus, once again, we find that the power output is very small, although it might be larger than in the White amplifier.

The disadvantages of pulsed operation and the provision of a magnetic field do not at the moment make it competitive with existing solid-state devices as a primary microwave source.

(ii) The acoustic amplification might be used to reduce the loss of a delay line, if the stability problem could be solved. However, the low losses of existing materials do not make this seem worthwhile (e.g., Ruby — 0.8 db/µsec. at 300°K and 1 kMc/s., Quartz — 0.0345 db/µsec. at 4°K and 3 kMc/s.).

VI. Discussion

There does not appear to be any immediate prospect of producing a practical solid-state traveling-wave tube on the lines of White's device. Its basic characteristics seem likely to be:

(a) Low power output
(b) High noise level
(c) Pulsed operation only
(d) Low efficiency
(e) Unstable operation
(f) Transducers a problem

The first four are basic, but the last two are possibly connected.

The high electromechanical coupling of Cadmium Sulphide makes it a very useful material for transducers, and the work of Quate and Foster shows how its properties can be used to advantage. As a delay line, however, it does not seem to be preferable to quartz or ruby.

While most of the difficulties enumerated above are alleviated at frequencies below U.H.F., efficient solid-state devices already exist for these frequencies. We do not, at the moment, see any advantages over them in the White amplifier.

The most interesting field for study appears to be the mechanism of the oscillations observed in Cadmium Sulphide near the knee of the current saturation curve. It is possible that these may be due to modes of oscillation other than those described by the "traveling-wave tube" model.

VII. Plans for the Next Quarter

The intention is to examine the current saturation phenomenon in more detail.

An amplifier is being constructed to operate in the 30-40 Mc/s. range. It will be used to gain experience of the experimental techniques involved, and to investigate the saturation phenomenon.

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