INTERACTION OF ELECTRONIC CURRENT WITH HYPERSONIC WAVES IN SOLIDS

RADIO CORPORATION OF AMERICA
RCA Laboratories
Princeton, New Jersey

Quarterly Progress Report No. 3
for the period
April 1, 1964 to June 31, 1964

Contract No. NAS 8-11120

Report Date: July 10, 1964

Prepared for

GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

Report prepared by: R. W. Smith and R. F. Mayo

OBJECTIVE

The objective of this work is to study the interaction of electronic current with hypersonic waves in solids, in particular in CdS, and to reach an understanding of the basic mechanisms for the acoustoelectric, and related, effects.

Discussion

Several problems connected with current saturation have been selected for more extensive study. The solution of these problems should provide a basis for a better understanding of the acoustoelectric effect. These problems are:

a) Detection and analysis of an rf component of current generated by a CdS crystal operated in the region of current saturation.

b) Measurement and analysis of the high frequency impedance of a CdS crystal operated in the region of current saturation.

c) The characterization and analysis of the large amplitude current oscillation observed when CdS is operated in the region of current saturation.

d) Geometric and crystallographic characterization of current saturation in CdS.

The status of each of these problems is reviewed below.

I - Detection of rf.

Hutson, McFee, and White[1] demonstrated that an ultrasonic noise signal could be detected by a piezoelectric receiver bonded to a CdS crystal, even though the transducer normally used to inject an ultrasonic signal was not excited. When current saturation was associated with electron bunching by the traveling wave amplification of thermal noise,[2] other means were sought to demonstrate the bunching within the crystal by methods that did not depend directly on converting the emerging energy into an electrical signal via the piezoelectric effect, as is the case with the bonded quartz receiver. Two non-acoustical detection schemes are immediately suggested;

1) detection of an rf signal, presumably associated with the bunching mechanism, by placing the crystal in a circuit containing a sensitive rf receiver; and 2) optical observation of the strain induced within the crystal by the amplification process. Both schemes have interesting and attractive features which encourage spending some time and effort exploring them.

Recalling the impressive pictures of photoelastic studies made of mechanical structures, it is more than just an academic question, why similar techniques should not permit the direct observation of the strain field in the crystal during acoustoelectric amplification. There are several variations of the optical method of detection, but all are based on observing a change in the index of refraction of light due to strain induced in the crystal. To date, satisfactory results have not been achieved by optical means. The optical method must in principal work, but, the reason for negative results are not obvious, nor are the details obvious for a better technique.

The situation is somewhat similar in the case of rf detection. The experiment is conceptually simple, but the experimental results are not clear cut or unambiguous, nor is there unanimity concerning either the analytical or experimental aspects of the problem. One of the major objectives of this work is to come to a better understanding of the problems involved.

The basic idea of the experiment is that bunched electrons moving through the CdS crystal should give rise to an rf component of current, predominately in the band of frequencies centered around the frequency of maximum acoustoelectric effect, i.e., 1 kMc. Furthermore, since $\sim$500 watts peak power is put into the crystal and approximately half of this power is dissipated through the acoustoelectric effect, the power appearing as rf should be easily detectable, allowing even for high losses due to severe internal attenuation.

The following outline, essentially chronological, may help to emphasize some of the problems that have come up. First we describe what we think is going on inside the crystal and what this might lead one to expect in terms of an rf signal that could be detected by a sensitive rf receiver.

A sheet of charge moving between plane-parallel plates (as sketched in Fig. 1) induces a current in an external circuit. In the acoustoelectric effect in CdS we will first consider the case where the only thermal elastic vibrations amplified are the ones corresponding to the maximum frequency for hypersonic waves given by the Hutson-White expression.[1] For any particular CdS crystal this frequency is determined mainly by its conductivity, and for the crystals we are interested in this corresponds to a maximum frequency $\sim$1 Kmc. Starting near the cathode 1 Kmc thermal vibrations gain energy from the electric field and increase in amplitude in moving across the crystal to the anode. Bunching of the free electrons in the troughs of the elastic wave is implicit in this type of traveling wave amplification. Inside the crystal there are sheets of charge, of greater-than-average density, spaced one wavelength, or $\sim 5\mu$, apart and moving through the crystal with the velocity of sound (See Fig. 1). If the crystal is properly mounted within a circuit containing a sensitive receiver tuned to 1 Kmc a signal should be observed when the crystal is operated in the saturation region, but no signal should be detected when the crystal is operated over the ohmic range. This then is the basic idea of the experiment. There are of course questions about the order of magnitude of the rf current expected and there are critical questions about how realistic the basic ideas are. The obvious way to answer most of these questions is to do the experiment. This has been done, but in general more questions have been generated than answered.

Over a year ago the experimental arrangement shown in Fig. 2 was set up and operated. The microwave part of the circuit is assembled with standard 50 Ω coaxial cable components. The voltage pulses go through a low-pass filter, to remove high-frequency components, before being applied across the CdS crystal. The crystal is mounted in a standard ceramic crystal cartridge. The dc component of current is lead to ground by the dc short, which presents a high impedance to the rf signal. The rf signal goes to the receiver through the dc block. The high-pass filter removes all frequencies below 500 Mc. The rf receiver is a conventional superheterodyne type, designed for low noise factor and pulse operation. Additional sensitivity could be obtained by an auxilary circuit which functions essentially as a phase sensitive detector.

The receiver can detect less than 10^{-12} watts pulse power. At saturation the voltage across the crystal is ~ 100 and the current through the sample is ~ 5 amps corresponding to ~ 500 watts pulsed power. The ratio of input power to minimum detectable power is $> 10^{14}$!

When the experiment was initially performed (over a year ago) the receiver was tuned to ~ 900 Mc and a low level signal (~ 90 dbm) was detected each time the crystal was operated beyond the threshold for saturation. No signal was detected below the threshold, nor was a signal detected when a resistor was substituted for the crystal. At first it was thought that this was the true rf signal expected from the bunched carriers moving in the crystal. In an attempt to cross check the work, several independent experiments were performed which suggested that the rf signal was a spurious effect, which could be ascribed to the generation of high-frequency harmonics from low frequency components in the exciting pulse operating on the non-linear part of the V-I curve of CdS. The two most convincing bits of data suggesting harmonic generation were; 1) a non-linear component made of "passive" elements (i.e., diodes and resistors) was substituted for the CdS crystal and was found to produce a 900 Mc signal, of form and magnitude quite similar to the CdS, and 2) 900 Mc harmonics could be generated from 1 Mc sine waves biased to the knee of a non-linear V-I curve.

About the same time C. Quate[3] described similar signals from CdS. Although Quate's experimental arrangement was somewhat different from the one shown in Fig. 2, and the conductivity of his crystals was different from ours, we subsequently confirmed that the two signals probably originated from the same effect. Quate did not discuss or investigate the possibility that the observed signals might be spurious.

Discouraged, a) by the evidence that the signal was probably not the one expected from bunching, b) by the very low level of the signal, and c) encouraged by more exciting results from experiments along a completely different line, the experimental work on rf detection was temporarily set aside. The one point that was definitely clear, however, was that in the frequency range where a high level signal might be expected, the observed level was extremely low. Where does all the power go? The answer to this enigma still lingers.

Recently, with the benefit of some additional experience, the rf experiments have been resumed, and preliminary results now suggest that the signals may <u>not</u> be due to the spurious effects we described above. The details of the data obtained so far, however, again raise more questions than are answered. Specifically the following observations have recently been made.

At 900 Mc the magnitude and form of the rf signal is essentially the same as the signal measured over a year ago. The temporal form of the rf signal is now better understood in terms of the rise time and duration of the exciting voltage pulse. That is, the magnitude and duration of the initial part of the rf is related to the high frequency content of the leading edge of the exciting pulse, this again is consistent with harmonic generation, however, for the flat part of the pulse that lasts for a long time (i.e., approaches dc in terms of this experiment) the rf signal is more or less constant. The latter is not consistant with harmonic generation.

The "passive" element which seemed to provide such convincing evidence for harmonic generation, has "lost face", since it is now realized that the diodes are not as passive as had been assumed. Also, the level of 1 Mc sine wave that must be introduced in order to give a harmonic signal equal to the observed signal is much higher than is likely to exist in the exciting pulse.

The spectral distribution of the rf as now observed is completely different from that which had been expected.

Curve A in Fig. 3 shows the spectral distribution expected, <u>a priori</u>, if the rf signal is directly related to the frequency dependence of the acoustoelectric amplification given by the small signal expression of Hutson and White. Curve B shows the preliminary data. The rf signal is low at 1 Kmc and increases to relatively high levels at 10 Mc. Measurements at lower frequencies are more complicated, because it is not as easy to make receivers that operate in this region with pulses. Work is in progress to extend the curves to lower frequencies, in order to see where the curve levels off, as it obviously must.

One particularly interesting thing from the curve may have some bearing on the high-level, low-frequency oscillations that can be excited in practically all CdS crystals exhibiting saturation. The onset of the oscillation varies rather abruptly with applied voltage. The frequency of the oscillations is 5-10 Mc and they may be coherent and essentially CW. See Fig. 4. The level of rf in this frequency range, before oscillation, is somewhat down from the level achieved during oscillation. This does suggest, however, that the oscillations "take off" from the relatively high level of rf already present at that frequency.

II - Impedance Measurements

The region of current saturation in CdS reflects a first-order change in the impedance of the crystal from its ohmic value. Since the amplification of hypersonic waves is a function of the dielectric relaxation time, the question of dependence of the impedance of the crystal over the range of frequencies active in the strong amplification mechanism is of considerable interest. The impedance has been measured at low frequencies (1-10 Mc) and was found to be a pure resistance corresponding to the value expected from the V-I curve. Systematic measurements at high frequencies have not been made, but, are definitely in order.

Experiments were attempted at 10 Kmc/sec, with a crystal post mounted in X-Band waveguide (See Fig. 5 of previous Report). The crystals which theory would lead us to think suitable for these high frequencies have very low resistivity. Thus, very high pulse currents are needed. A hard-tube pulse modulator capable of producing pulse currents of over 60 amps and voltages of up to 15 kv was constructed. A polished CdS post was pulsed in the waveguide, but before the knee of the V-I curve could be attained, flash-over occured down the surface of the crystal. This crystal was cleaned and re-polished, and other crystals prepared. Flash-over is caused usually by "tracking" down the surface of the crystal, i.e. a small layer of dirt on the surface can provide a path for current. The resultant local heating when this layer breaks down can damage the crystal severely, and even split it. Two long posts were lost in this way before any useful work could be done with them. Since the long crystals took some time to prepare, a new form of waveguide mount was adopted. This (see Fig. 5) uses smaller crystals, of which a supply was already available.

Impedance measurements were attempted, but no change in the impedance of the crystal could be detected. Neither could any X-Band power, coherent or incoherent, be detected in the waveguide.

Two improvements in these experiments are being carried out. A resonant cavity if being made to hold the crystal. It is hoped that this will concentrate the rf fields at the crystal and make easier the detection of any impedance change. If this still produces no results, a low-noise travelling wave tube will be used to detect radiation from the crystal. We feel that some effort in the latter direction would be worthwhile in order to investigate the collective-phonon theory of Prohofsky, mentioned in previous Reports, which predicts a rise in the noise level in a saturated CdS crystal at 10-100 Kmc/sec, (i.e., where $h\nu = m^* v_s^2$). The noise figures of T.W.T.'s in this region are not as good as those at 3 Kmc/sec. where 1.0 db. noise figures have been reached, and this may prevent any really sensitive measurements, e.g. noise figures of over 10 db. are normal for these frequencies.

A mathematical treatment of the impedance problem is given in Appendix A. This is carried as far as possible without recourse to a computer. It was thought inadvisable to devote more time to this until some experimental data had been obtained, and it was known whether any detectable effects could be seen. Nevertheless, these calculations lead us to hope for positive results.

III - Large-Amplitude Oscillations

Large amplitude, low frequency coherent oscillations have been observed in CdS from the time current saturation was first observed. In fact, practically all CdS crystals examined have oscillated during some stage of operation. One of the most impressive features is the high power level associated with the oscillation. We will not describe in this report, all of the characteristics that have been noted. It should be pointed out, however, that there may be several types of oscillations, which in many respects appear quite similar. In view of the large magnitude of the oscillations, work is in progress to obtain more experimental data, in order to understand the mechanisms involved. See Fig. 4.

IV - Geometric and Crystallographic Characterization

Samples of various sizes and crystallographic orientations are being prepared in order to obtain a better understanding of the influence of these factors in the acoustoelectric effect. One question we would like to answer is that of what modes of elastic vibrations are amplified. Geometry may also be an important factor in the large amplitude oscillations described above.

Appendix A - The R.F. Impedance of a CdS Post with a D.C. Applied Electric Field

We derive, formally, an expression for the r.f. impedance seen between the two ends of a CdS post which is considered to be sufficiently broad for a one-dimensional treatment to be a good approximation, i.e., edge effects can be neglected. It is further assumed that no acoustic energy is coupled out of the crystal, and that the electric field vanishes at the ends of the crystal. The latter condition is probably an oversimplification because of the complex nature of so-called "ohmic" contacts, but it expresses the physically reasonable condition that r.f. electric waves incident upon such a surface will be totally reflected. Some figures to justify the acoustic boundary condition can be quickly calculated. The acoustic impedance of a material is defined as the product of its density and the velocity of sound in it. For air this is 30 gm. sec.^{-1} cm^{-2}, and for Cadmium Sulphide it is approximately 9×10^5 gm. sec.^{-1} cm^{-2}. These figures show that there is a very considerable mismatch, and express the fact that there will be no stress at the ends of the crystal since air is too light to exert any reaction on the ends of the crystal.

Our basic equations are *:

$$I(t) = \left[\epsilon \left\{ \frac{\partial E_1}{\partial t} + \mu E_0 \frac{\partial E_1}{\partial x} - D_e \frac{\partial^2 E_1}{\partial x^2} \right\} + \rho_0 \mu E_1 \right] \quad \text{(C1)}$$

$$+ e \left[\frac{\partial S_1}{\partial t} + \mu E_0 \frac{\partial S_1}{\partial x} - D_e \frac{\partial^2 E_1}{\partial x^2} \right]$$

= total r.f. current.

---

* Strictly, the total current in a one-dimensional system is zero, but in writing this equation we are attempting, in effect, a perturbation analysis and neglecting the transverse derivatives of the E-field.

$$\rho_m \frac{\partial^2 S_1}{\partial t^2} = c \cdot \frac{\partial^2 S_1}{\partial x^2} - e\frac{\partial^2 E_1}{\partial x^2} \tag{C2}$$

Eliminating the strain, S_1, we get $I(t)$ in terms of the electric field E_1:

$$\left[c\frac{\partial^2}{\partial x^2} - \rho_m\frac{\partial^2}{\partial t^2}\right]I(t) = \left(c\frac{\partial^2}{\partial x^2} - \rho_m\frac{\partial^2}{\partial t^2}\right)\left[\epsilon\left\{\frac{\partial E_1}{\partial t} + \mu E_0\frac{\partial E_1}{\partial x} - D_n\frac{\partial^2 E_1}{\partial x^2}\right\} + \rho_0\mu E_1\right]$$

$$+ e^2\left\{\frac{\partial}{\partial t} + \mu E_0\frac{\partial}{\partial x} - D_n\frac{\partial^2}{\partial x^2}\right\}\frac{\partial^2 E_1}{\partial x^2}$$

Assume $\frac{\partial}{\partial t} = j\omega$, then:

$$\frac{\omega^2}{v_s^2}I(t) = \left(\frac{\partial^2}{\partial x^2} + \frac{\omega^2}{v_s^2}\right)\left(\epsilon\left\{j\omega E_1 + \mu E_0\frac{\partial E_1}{\partial x} - D_n\frac{\partial^2 E_1}{\partial x^2}\right\} + \rho\mu_0 E_1\right)$$
$$+ \epsilon K^2\left\{j\omega + \mu E_0\frac{\partial}{\partial x} - D_n\frac{\partial^2}{\partial x^2}\right\}\frac{\partial^2 E_1}{\partial x^2} \tag{C3}$$

where $K^2 = \frac{e^2}{\epsilon c}$, and $v_s = \sqrt{\frac{c}{\rho_m}}$ = velocity of sound.

The particular integral is $I = (j\omega\epsilon + \rho_0\mu)E$. The complementary function is $E_1 = A_1 e^{-\Gamma_1 x} + \text{-----} + A_4 e^{-\Gamma_4 x}$ where $\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4$ are determined from White's calculations for the case I = 0. Thus the solution has the form:

$$E_1(x) = \frac{I(t)}{j\omega\epsilon + \rho_0\mu} + A_1 e^{-\Gamma_1 x} + \text{-----} + A_4 e^{-\Gamma_4 x} \tag{C4}$$

If the length of the crystal is a, then we have the boundary conditions: $E_1(0) = E_1(a) = 0$ and $S_1(0) = S_1(a) = 0$. Also we have an expression for the r.f. voltage between the ends of the crystal:

$$V_{\text{applied}} = -\int_0^a E\,dx \tag{C5}$$

From Eq. (A2) we see that the strain wave associated with the electric field $E = Ae^{-\Gamma x}$ is:

$$S_1 = \frac{A \cdot \frac{e}{c} \cdot e^{-\Gamma x}}{1 + \omega^2/\Gamma^2 v_s^2} \quad \text{(C6)}$$

Thus the total strain is given by:

$$S(x) = \frac{A_1 \cdot \frac{e}{c} \cdot e^{-\Gamma_1 x}}{1 + \omega^2/\Gamma_1^2 v_s^2} + \text{------} + \frac{A_4 \frac{e}{c} e^{-\Gamma_4 x}}{1 + \omega^2/\Gamma_4^2 v_s^2} \quad \text{(C7)}$$

Using the boundary conditions we get:

$$V_{app} = \frac{A_1}{\Gamma_1}(e^{-\Gamma_1 a} - 1) + \frac{A_2}{\Gamma_4}(e^{-\Gamma_2 a} - 1) + \text{----} + \frac{Ia}{j\omega\epsilon + \sigma}$$

$$0 = A_1 e^{-\Gamma_1 a} + A_2 e^{-\Gamma_2 a} + \text{----} + \frac{I}{j\omega\epsilon + \sigma}$$

$$0 = A_1 + A_2 + \text{----} + \frac{I}{j\omega\epsilon + \sigma}$$

$$0 = \frac{A_1 e^{-\Gamma_1 a}}{1 + \frac{\omega^2}{\Gamma_1^2 v_s^2}} + \text{-------} + \frac{A_4 e^{-\Gamma_4 a}}{1 + \omega^2/\Gamma_4^2 v_s^2}$$

$$0 = \frac{A_1}{1 + \frac{\omega^2}{\Gamma_1^2 v_s^2}} + \text{-------} + \frac{A_4}{1 + \frac{\omega^2}{\Gamma_4^2 v_s^2}} \quad \text{(C8)}$$

Defining $Z_0 = a/j\omega\epsilon + \sigma$, and eliminating $A_1 --- A_4$ we obtain the determinant:

$$
\begin{vmatrix}
V_{app} - I Z_0 & \frac{1}{\Gamma_1}\left(e^{-\Gamma_1 a} - 1\right) & \frac{1}{\Gamma_2}\left(e^{-\Gamma_2 a} - 1\right) & \frac{1}{\Gamma_3}\left(e^{-\Gamma_3 a} - 1\right) & \frac{1}{\Gamma_4}\left(e^{-\Gamma_4 a} - 1\right) \\
-\frac{I Z_0}{a} & e^{-\Gamma_1 a} & e^{-\Gamma_2 a} & e^{-\Gamma_3 a} & e^{-\Gamma_4 a} \\
-\frac{I Z_0}{a} & 1 & 1 & 1 & 1 \\
0 & \dfrac{e^{-\Gamma_1 a}}{1 + \frac{\omega^2}{\Gamma_1^2 v_s^2}} & \dfrac{e^{-\Gamma_2 a}}{1 + \frac{\omega^2}{\Gamma_2^2 v_s^2}} & \dfrac{e^{-\Gamma_3 a}}{1 + \frac{\omega^2}{\Gamma_3^2 v_s^2}} & \dfrac{e^{-\Gamma_4 a}}{1 + \frac{\omega^2}{\Gamma_4^2 v_s^2}} \\
0 & \dfrac{1}{1 + \frac{\omega^2}{\Gamma_1^2 v_s^2}} & \dfrac{1}{1 + \frac{\omega^2}{\Gamma_2^2 v_s^2}} & \dfrac{1}{1 + \frac{\omega^2}{\Gamma_3^2 v_s^2}} & \dfrac{1}{1 + \frac{\omega^2}{\Gamma_4^2 v_s^2}}
\end{vmatrix} = 0 \, ,
\tag{C9}
$$

After some lengthy, but straightforward, manipulation, this reduces to the following expression for the r.f. impedance Z:

$$\frac{Z}{Z_o} = \frac{V}{I Z_o} = 1 + \frac{\begin{vmatrix} (e^{\Gamma_1 a}-1)\frac{\Gamma_1}{a}\left(1+\frac{\omega^2}{\Gamma_1^2 v_s^2}\right) & \\ (e^{-\Gamma_1 a}-1) & \\ \Gamma_1^2 e^{-\Gamma_1 a} & \text{-------} \\ \Gamma_1^2 & \end{vmatrix}}{\begin{vmatrix} e^{-\Gamma_1 a}\cdot\frac{\omega^2}{v_s^2} & \\ 1 & \\ \Gamma_1^2 e^{-\Gamma_1 a} & \text{-------} \\ \Gamma_1^2 & \end{vmatrix}} \qquad \text{(C10)}$$

It would require a computer calculation to use this result for a practical example. But one point can be made. The determinant in the denominator is related to the solution for A_1, A_2, A_3, A_4 with no externally applied r.f. voltage. The vanishing of this determinant is the condition for non-zero solutions for A_1 --- A_4 to exist under these circumstances. In other words, if this determinant vanishes, the crystal will break into oscillation.

Since theory leads us to expect that this will happen when the d.c. electron drift velocity is near the velocity of sound, we are once more faced with the question of why this is not observed in practice.

Nevertheless, it is clear that if the theory is anywhere near to describing the physical reality, the impedance should be strongly dependent upon the d.c. bias field, and impedance measurements should give us some idea of how near the crystal is to oscillation.

The effect of external impedances on the oscillation conditions can be found, in principle, from Eqs. (C8). If an impedance Z_L is connected across the crystal, we can eliminate V_{app} from these equations, and from the determinant (C9). If this determinant can be made to vanish then we can solve for non-zero values of I, A_1, A_2, A_3, A_4, with no external generator in the circuit, i.e., the device will oscillate.

Any such oscillations would be bound to occur at a frequency near to $\omega_0 = \left[\frac{\sigma}{\epsilon} \cdot \frac{v_D^2}{D_e} \right]^{1/2}$. For this reason it is not considered that this is an explanation of the oscillations occasionally seen in the current through CdS crystals near the knee of the V-I curve. Their frequency is much lower than ω_0 and shows a dependence on the transit time of electrons through the crystal.

References

1. A. R. Hutson, J. H. McFee, and D. L. White, Phys. Rev. Letters 7, 237 (1961).

2. R. W. Smith, Phys. Rev. Letters 9, 527 (1962).

3. K. Blotekjaer and C. F. Quate, M. L. Report 1057, Microwave Laboratory, Stanford University, July 1963. Also Proc. IEEE 52, 360 (1964).

Figure Captions

Fig. 1 Schematic drawing showing basic idea of rf experiment.

Fig. 2 Schematic circuit for rf experiment.

Fig. 3 RF power v.s. frequency.

Fig. 4 Low frequency (~ 5 mc) high level oscillation in current in CdS.

Fig. 5 Impedance experiment. Crystal mount in waveguide.

specific gravity	sp gr	ton	spell out
specific heat	sp ht	tons per square inch	tsi
specific volume	sp vol	Torricelli	torr
square	sq	triton(s)	t
square centimeter	cm^2	ultra high frequency	uhf
square foot	ft^2	ultraviolet	uv
square inch	$in.^2$	United States Pharmacopeia	USP
square kilometer	km^2	versed sine	vers
square meter	m^2	versus	vs
square micron	μ^2	very high frequency	vhf
square millimeter	mm^2	Vickers hardness number	VHN
square root of mean square	rms	volt	v
standard cubic feet per minute	scfm	volt-ampere	va
standard temperature and pressure	STP	volt-coulomb	spell out
steradians	sterad	volume percent	vol %
symmetrical (in organic compounds)	sym-	Watt	w
tangent	tan	watthour	whr
that is	i.e.	week (-ly)	spell out
thousand pounds	kip	weight	wt
thousand ton(s)	kt	weight percent	wt %
		yard	yd
		year	yr

The following quantities may be used with any of the preceding abbreviations or symbols:

Quantity	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	K
10^{2}	hecto	H
10^{1}	deca	D
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

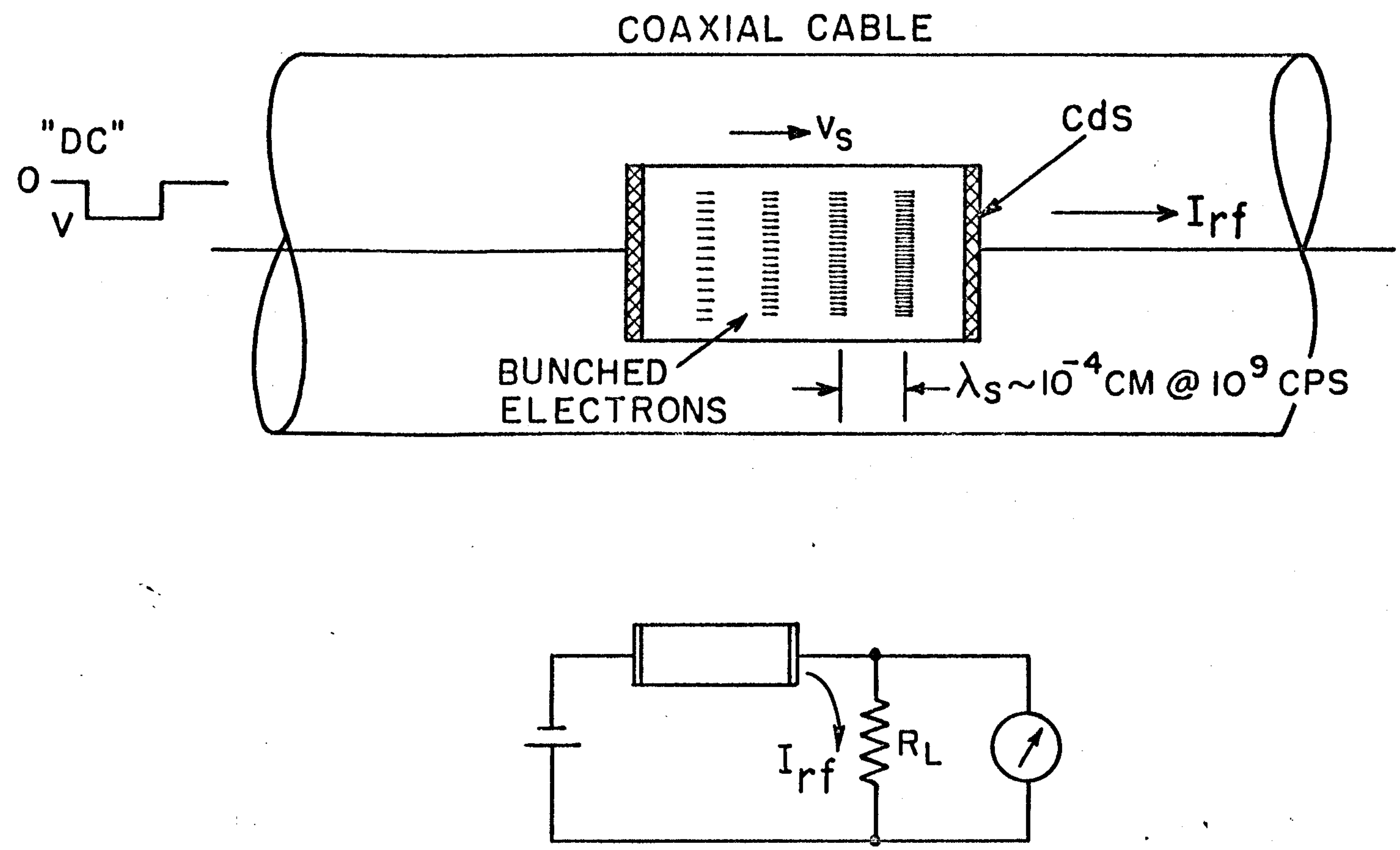

COAXIAL CABLE
"DC"
0
V
$\rightarrow V_S$
CdS
$\rightarrow I_{rf}$
BUNCHED ELECTRONS
$\lambda_S \sim 10^{-4}$ CM @ 10^9 CPS
I_{rf}
R_L

FIG. 1

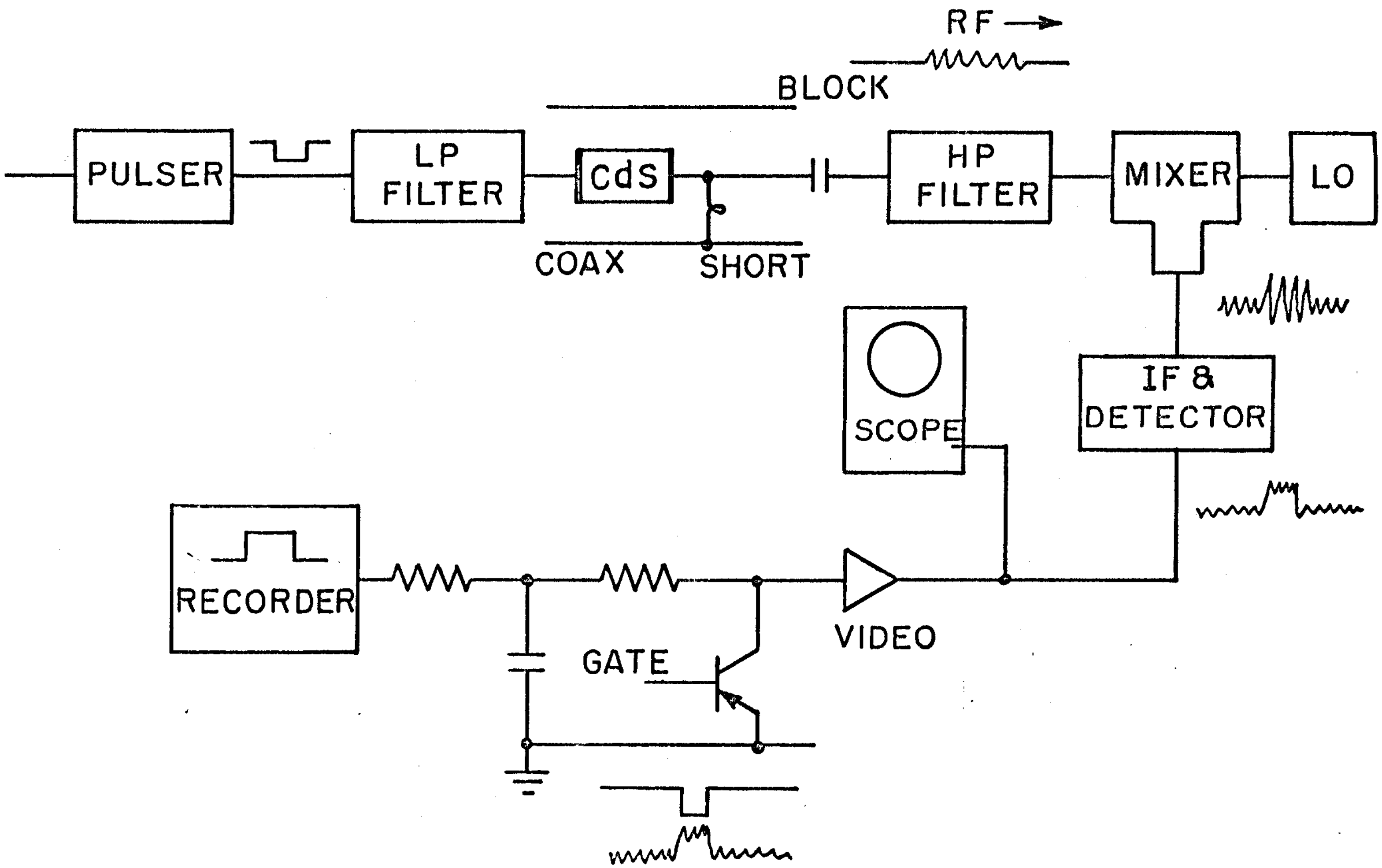
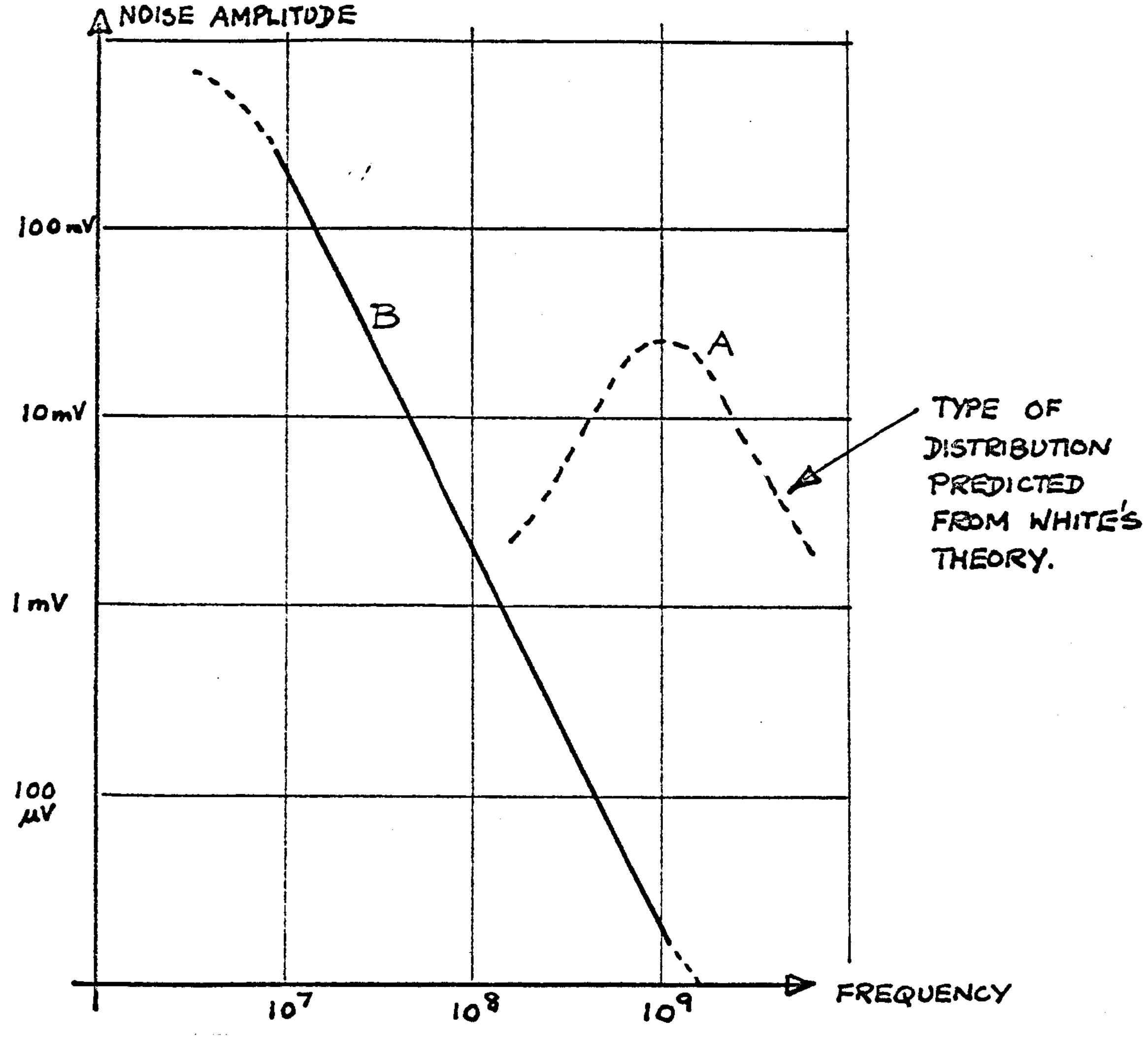
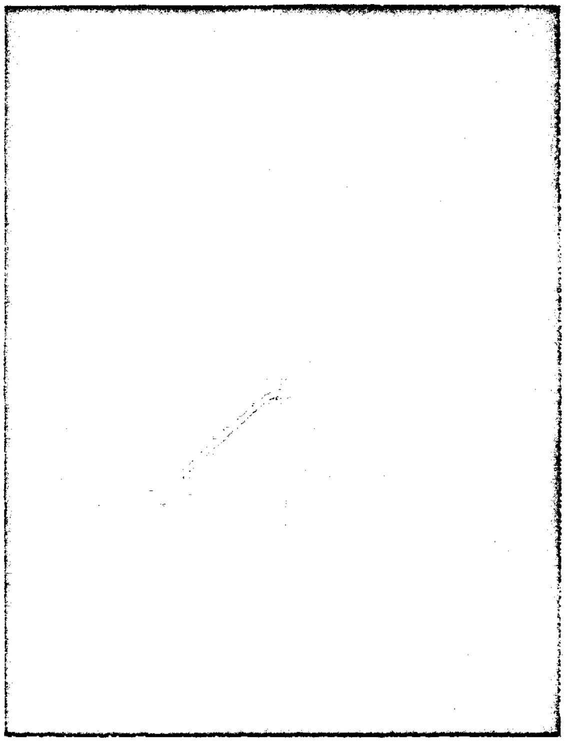
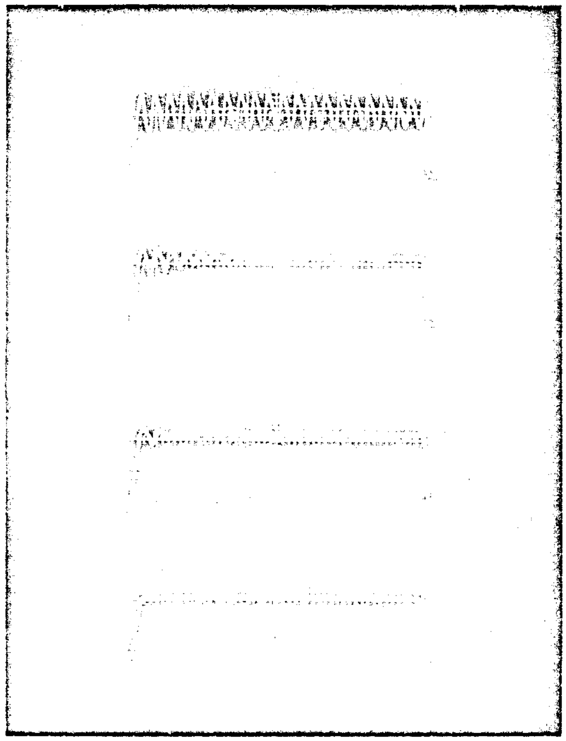

RF
BLOCK
PULSER
LP FILTER
CdS
COAX
SHORT
HP FILTER
MIXER
LO
IF & DETECTOR
SCOPE
VIDEO
RECORDER
GATE

FIG. 2.

Fig. Nº 2 NOISE SPECTRUM OBSERVED BY SMITH & OLDAKOWSKI.







V-I

CURRENT OSCILLATIONS.

Fig. 4.

Appendix C
Greek Alphabet

Alpha (a).........Α α or ɑ
Beta (b)..........Β β or ϐ
Gamma (g)........Γ γ
Delta (d)..........Δ δ or ∂
Epsilon (e)........Ε ϵ
Zeta (z)...........Ζ ζ
Eta (h)...........Η η
Theta (th).........Θ θ or ϑ
Iota (i)...........Ι ι
Kappa (k).........Κ κ or ϰ
Lambda (l)........Λ λ
Mu (m)...........Μ μ
Nu (n).............Ν ν
Xi (x)..............Ξ ξ
Omicron (o)........Ο ο
Pi (p)..............Π π
Rho (r)............Ρ ρ
Sigma (s)...........Σ σ or ς
Tau (t).............Τ τ
Upsilon (u).........ϒ υ
Phi (ph)............Φ φ or ϕ
Chi (ch)............Χ χ
Psi (ps)............Ψ ψ
Omega (o)..........Ω ω

α β γ δ ϵ ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω

α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ ϕ χ ψ ω

Fig. 5