

## MEASUREMENTS ON POWER-CONVERSION GAIN AND NOISE RATIO OF THE 1N26 CRYSTAL RECTIFIERS

by A. DYMANUS \*) and A. BOUWKNEGT

Fysisch Laboratorium der Rijksuniversiteit, Utrecht, Netherlands.

### Synopsis

Measurements have been performed on power conversion gain  $G$  and noise ratio  $n$  of a number of 1N26 silicon rectifiers (Sylvania Co., U.S.A.) using well-known techniques. The noise ratio has been investigated both with microwave excitation ( $10^{-6}$ – $10^{-3}$  W at 24 GHz) and with DC-excitation by currents up to  $100\text{ }\mu\text{A}$  in the forward direction and up to  $20\text{ }\mu\text{A}$  in the backward direction. The results (relative error 5–15 per cent, estimated absolute error 25–30 per cent for microwave excitation and about 15 per cent for DC-excitation) confirm the inverse-frequency dependence of  $n$  in the frequency region from 100 Hz–455 kHz and the independence of  $G$  ( $\sim 0.2$  for sensitive rectifiers) of microwave power at powers higher than about  $3 \cdot 10^{-4}$  W. There is, however, a considerable discrepancy between the present results and the results of other investigators on  $G$  at powers below  $\sim 3 \cdot 10^{-4}$  W, and on power and DC-current dependence of  $n$  for microwave and DC-excitation, respectively. A possible explanation is suggested for the discrepancy of the power dependence of  $n$ . However, no explanation can be given of the saturation of  $n$  at DC-excitation by currents in the forward direction through sensitive rectifiers. No  $n$ -saturation was observed at microwave excitation.

1. *Introduction.* Performance of a microwave crystal rectifier as power detector is well described by its noise ratio  $n$  and its power conversion gain  $G$ . In the case of rectifiers used at the specific radar wavelength (3 and 10 cm) the desired information about these quantities is usually found in Vol. 15 of the M.I.T. Radiation Laboratory Series <sup>1)</sup>. Quantitative information about the silicon 1N26 rectifier (Sylvania Co., U.S.A.), widely used in microwave spectroscopy, is scarce in the cited reference and mostly concerned with the mixer performance. Moreover, the expressions for  $n$  and  $G$  found in the physical literature are frequently conflicting <sup>1–4)</sup>.

The present investigation was undertaken in order to clear up the situation and to provide reasonably accurate values of  $n$  and  $G$  desired for the design of microwave spectrometers and for the estimate of spectrometer sensitivity.

2. *Definitions.* When a crystal rectifier is used as mixer in a heterodyne detection scheme the conversion gain,  $G_{IF}$ , at a given local oscillator ( $LO$ )

---

\*) Present address: Harvard University, Cruft Laboratory, Cambridge, Mass, U.S.A.

power level, is usually (Ref. 1, p. 128) defined as:

$$G_{IF} = P_{IF}/P_S, \quad (1)$$

where,  $P_{IF}$  is the  $IF$  output power, and  $P_S$  the microwave (signal) input power.

It can readily be shown that in the square law region of the rectifier response, in which the rectified current  $i$  is connected to the incident wave voltage  $V$  by the relation:

$$i = \beta V^2 \quad (2)$$

with a constant  $\beta$  independent of  $V$ , the definition (1) is equivalent to:

$$G_{DC} = \Delta P_{DC}/\Delta P = G, \quad (3)$$

assuming that proper matching conditions are satisfied both for (1) and for (3). In the definition (3),  $\Delta P_{DC}$  is the change of the output  $DC$ -power  $P_{DC}$  for a given change  $\Delta P$  of the microwave input power  $P$  to the rectifier. The power conversion gain as defined in (3) is thus equal to the slope of the  $P_{DC}$  vs.  $P$  curve. It is assumed in this paper that the definitions (1) and (3) are equivalent at all power levels as used in the present investigation. The validity of this assumption will be discussed in Par. 5.

The noise ratio  $n^*$  is defined (Ref. 1, p. 30) as the ratio of the available noise output power  $P_n$  of the rectifier to that of a resistor at room temperature, both referred to unit frequency interval. The latter power is equal to  $kT$ , where  $k$  is Boltzmann's constant and  $T$  the absolute temperature. The noise ratio is thus:

$$n = P_n/(kT). \quad (4)$$

The power  $P_n$  is determined usually by measuring the mean noise voltage squared,  $\overline{V_{XT}^2}$ , at the output of a narrow band amplifier connected across the rectifier load impedance  $Z_L$ . Assuming that:

- i) the amplifier band-width (centre frequency  $\nu_0$ ) is small enough to regard  $\overline{V_{XT}^2}$  as a constant ( $= \overline{V_{XT}^2}(\nu_0)$ ) throughout the band-width,
  - ii) the noise figure of the amplifier is equal to unity,
  - iii) the input impedance of the amplifier is very large compared to  $Z_L$ , and
  - iv) that  $Z_L$  is matched to the output impedance  $Z$  of the rectifier,
- the expression (4) can be written:

$$n = \frac{\overline{V_{XT}^2}(\nu_0)}{kTG_{\max}^2RB}. \quad (5)$$

Herein,  $B$  is the effective noise band-width of the amplifier,  $G_{\max}$  its maximum voltage gain, and  $R$  is the resistive component of  $Z$ , also called dynamic  $DC$ -resistance of the rectifier.

\*) In Ref. 1, p. 30 this quantity is called "noise temperature" and is denoted by  $T$ .

3. *Experimental apparatus.* A simplified diagram of the experimental set-up is given in Fig. (1a). The excitation circuit for microwave measurements consisted of a frequency stabilized 2K33 klystron oscillator connected to the rectifier through a set of variable attenuators. The latter served to adjust the input power to the rectifier, the absolute power level being determined with a calibrated monitor rectifier. Matching of the rectifier to the input guide was controlled with a standingwave meter. For the measurements on  $n$  at *DC*-excitation an excitation circuit, consisting of a current source having an effective zero impedance at noise frequencies in the *AF* and *RF* region, was connected to the voltmeter terminals of the rectifier load circuit (Fig. (1b)). In the latter circuit the resistive loading of the rectifier could be chosen with a switch ( $S$ ) from a set of nine values between 0 and  $2 \cdot 10^5 \Omega$ . All resistors were wire-wound and non-inductive in order to eliminate extra noise and frequency dependent loading of the rectifier.

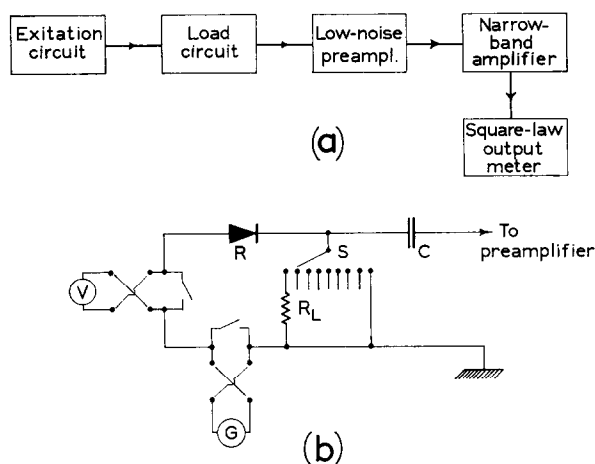


Fig. 1.

(a) Simplified diagram of the experimental apparatus.

(b) Schematic drawing of the rectifier load circuit:

$C$  = condenser ( $\sim 12 \mu\text{F}$ ),  $G$  = galvanometer (internal resistance  $\sim 10 \Omega$ ),  $R$  = rectifier,  $R_L$  = load resistors (9 values from 0– $2 \cdot 10^5 \Omega$ ),  $S$  = switch,  $V$  = voltmeter.

The noise voltage built up across the rectifier load resistor was first amplified in a low-noise preamplifier followed by a narrow band amplifier and then applied to a square law output meter. The latter was a slight modification of the circuit of Nielsen and van der Ziel<sup>5)</sup>. The square law element of this circuit was a set of thermistors, the noise voltage being applied to them through a *DC*-coupled cathode follower. The thermistors were immersed in an oil bath kept at a constant temperature to within about  $0.2^\circ\text{C}$ . Drift of the output meter was reduced in this way to a negligibly small amount

The time constant was adjustable from 3 to 60 sec. The output meter was calibrated with a known sinoidal voltage and the deviation from the square law response amounted to less than two per cent.

The  $AF$  preamplifier was a low noise battery operated amplifier having an input impedance of about 200 k $\Omega$ . For the measurements at 455 kHz this preamplifier was replaced by a low noise cascode circuit similar to the one described by Good <sup>6</sup>). A high input impedance ( $\sim 200$  k $\Omega$ ) of the preamplifier was obtained by using an input  $LC$ -network resonating at 455 kHz.

The  $AF$  narrow band amplifier was a commercially available product (Bruel & Kjaer Co., Denmark, type 2105) with a selectivity adjustable from 20 to 40 db/octave. The latter selectivity was generally used in this investigation. At 455 kHz a conventional amplifier has been used equipped with a magnetostriction filter (Collins Co., U.S.A.) yielding an almost square response curve about 1200 Hz wide. Both narrow band amplifiers were equipped with precision attenuators which allowed reduction of the gain up to 60 db in steps of about 5 db. The gain of the amplifiers was adjusted with these attenuators such that at all noise input voltages the reading of the output meter did not vary more than by about a factor of six. In this way noise powers differing even by a factor of  $10^7$  could be measured accurately with only two sensitivity ranges of the output meter. The value of  $G_{\max}$  was obtained from the setting of the attenuator and the known over all gain at zero attenuation. The latter gain was determined in the ordinary way.

The effective noise band width,  $B$ , was determined with a diode (type 5722, Sylvania) noise source or by measuring the overall gain point by point and integrating graphically the resulting gain *vs.* frequency curve.

4. *Results.* Measurements have been performed on eight rectifiers arbitrarily chosen from a set of rectifiers which have not been used previously. The rather low excitation limits: 1 mW at microwave excitation, and 100  $\mu$ A in the forward and 20  $\mu$ A in the backward direction at the excitation by  $DC$  currents, have been set in order to prevent any deterioration of the rectifier properties. At microwave measurements all rectifiers were tuned for zero reflection. This tuning depended on  $P$  and  $R_L$ , and at a given  $P$  and  $R_L$  it was found to coincide with tuning for maximum rectified current or for maximum noise output voltage.

a) *Power conversion gain.* The power conversion gain and its dependence on the microwave power level was determined from the  $P_{DC}$  *vs.*  $P$  relation according to Eq. (3). As  $P_{DC}$  in this relation was taken the maximum  $DC$  output power. The latter was determined in the ordinary way by measuring  $P_{DC}$  at several values of the load resistor  $R_L$ .

At the input powers below  $10^{-4}$  W,  $G$  was found to be proportional to  $P$ :

$$G = SP, \quad (6)$$

with the constant  $S$  varying from about 100 to about  $500 \text{ W}^{-1}$ . It was quite remarkable that  $S$  of all investigated rectifiers was close either to  $500 \text{ W}^{-1}$  (sensitive-) or to  $100 \text{ W}^{-1}$  (insensitive rectifiers). At the input powers higher than about  $3 \cdot 10^{-4}$  W,  $G$  was a constant:

$$0.01 < G < 0.25,$$

with a less pronounced distinction between sensitive and insensitive rectifiers than at low powers.

A set of typical  $G$  vs.  $P$  curves is shown in Fig. (2).

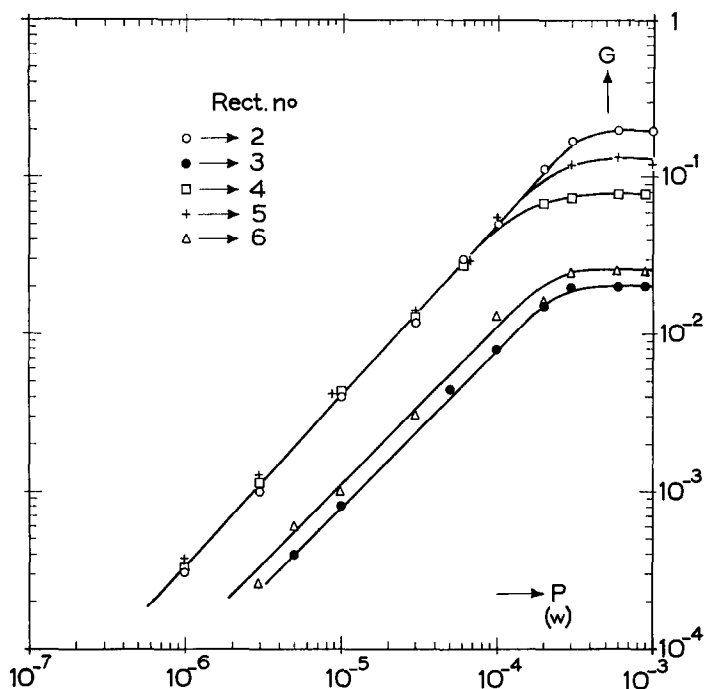


Fig. 2. The power conversion gain  $G$  as a function of the input power to the rectifier.

b) Noise ratio with microwave excitation. The results of measurements on  $n$  with microwave excitation are well summarized in the expression:

$$n = C \frac{P^\alpha}{\nu_0} + 1, \quad (7)$$

with

$$0.9 < \alpha < 1.1,$$

and

$$3 \cdot 10^{10} < C < 2 \cdot 10^{11} \text{ W}^{-1} \text{ Hz}.$$

The expression (7) was obtained from (5) by substituting in the latter the measured values of  $B$ ,  $G_{\max}$ , and the maximum value of

$$\overline{V_{XT^2}(v_0)}/R_L \quad (\equiv \overline{V_{XT^2}(v_0)}/R)$$

at the given frequency  $v_0$  and power  $P$ . The maximum value of  $\overline{V_{XT^2}(v_0)}/R_L$  was obtained in the ordinary way from the measurements on the  $R_L$  dependence of  $\overline{V_{XT^2}(v_0)}$ . All measurements have been corrected for the amplifier noise according to:

$$\overline{V_{XT^2}(v_0)} = \overline{V_U^2(v_0)} - \overline{V_A^2(v_0)},$$

where,  $\overline{V_A^2(v_0)}$  and  $\overline{V_U^2(v_0)}$  are the mean noise output voltage squared of the amplifier only and of the amplifier and rectifier together, respectively.

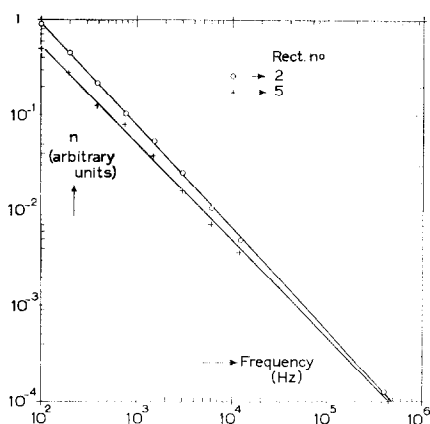


Fig. 3. The frequency dependence of the noise ratio  $n$  of rectifier No. 2 excited by  $10^{-4}$  W. of microwave power, and of rectifier No. 5 excited by a DC current of  $25 \mu\text{A}$  in the forward direction.

The inverse-frequency dependence of  $n$  was found to hold from 100 Hz up to 455 kHz (Fig. (3)). Generally, the insensitive rectifiers were found to be less noisy than the sensitive ones. The  $n$  vs.  $P$  curves of the eight investigated rectifiers are given in Fig. (4).

c) Noise ratio with DC-excitation. The dependence of  $n$  on the DC-current through the rectifier and on the frequency  $v_0$  was investigated in the same way as with microwave excitation. At all currents  $\overline{V_{XT^2}(v_0)}$  was measured at several values of the load resistor  $R_L$  and the maximum value of  $\overline{V_{XT^2}(v_0)}/R_L$  was then used to obtain  $n$  from Eq. (5).

The dependence of  $\overline{V_{XT^2}(v_0)}$  on the forward DC current  $I_+$  through the rectifier and on the resistive loading is shown in Figs. (5a) and (5b) for a sensitive and an insensitive rectifier, respectively.

There is a striking difference in the appearance of curves in these figures. Whereas,  $\overline{V_{XT}^2}(\nu_0)$  in Fig. (5b) is roughly proportional to  $I_+^{3/2}$  at all values

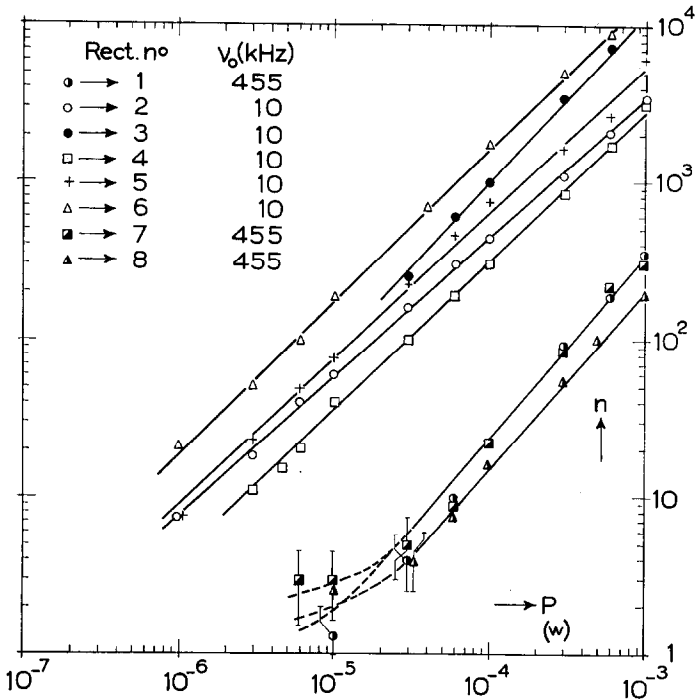


Fig. 4. The dependence of the noise ratio  $n$  on the microwave power  $P$  at two centre frequencies  $\nu_0$  of the amplifier noise bandwidth.

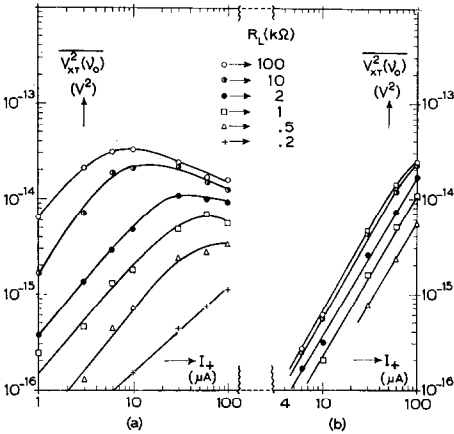


Fig. 5.

- (a) The noise output voltage squared  $\overline{V_{XT}^2}(\nu_0)$  built up across various load resistors  $R_L$  as a function of the forward current  $I_+$  through a typical sensitive rectifier at  $\nu_0 = 10$  kHz.
- (b) Same as (a) but for a typical insensitive rectifier.

of  $R_L$ , it tends in Fig. (5a) to a maximum value and then decreases with increasing  $I_+$ . The current at which  $\overline{V_{XT^2}(v_0)}$  attains its maximum value depends on  $R_L$ . For backward DC currents,  $I_-$ , through the rectifiers,  $\overline{V_{XT^2}(v_0)}$  was roughly proportional to  $I_-^2$  at all values of  $R_L$ , both for sensitive and insensitive rectifiers.

Three curves of  $n$  vs.  $I_+$  at the frequency of 10 kHz are shown in Fig. (6a). The curve 1 is typical for insensitive rectifiers, the curves 2 and 3 for sensitive ones. For all insensitive rectifiers  $n$  was proportional to  $I_+^2$ . The sensitive rectifiers showed a rather large spread in the  $I_+$  dependence of  $n$ , particularly with respect to the saturation at higher currents.

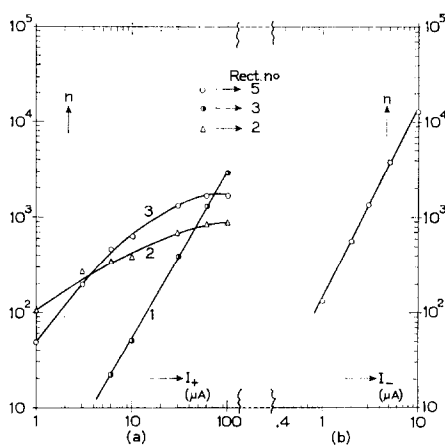


Fig. 6.

- (a) The noise ratio  $n$  of two typical sensitive rectifiers (curves Nos. 2 and 3, rectifiers Nos. 2 and 5, respectively) and of a typical insensitive rectifier (curve No. 1, rectifier No. 3) as a function of the forward current  $I_+$  through the rectifier at  $v_0 = 10$  kHz.
- (b) A typical curve of  $n$  as a function of the backward current  $I_-$ .

The noise ratio at backward currents (Fig. (6b)) was roughly proportional to  $I_-^\gamma$  with  $\gamma$  varying from 2 to 2.6 for all rectifiers. For a given current  $I_-$ ,  $n$  was 10–100 times larger than for the same forward current.

5. *Discussion.* The estimated RMS-error in the absolute value of  $G$  is about 25 per cent and is almost completely due to the uncertainty of the absolute value of microwave power. Relative power measurements could be performed with an accuracy of about four per cent. The error in the relative values of  $G$  is 5–8 per cent. The estimated total error of  $n$  is about 30 per cent at microwave excitation, and about 15 per cent at DC-excitation. The major contributions to the latter error stem from the error in  $G_{\max}^2$  ( $\sim 4$  per cent), in  $B$  ( $\sim 5$  per cent), and in the maximum value of  $\overline{V_{XT^2}(v_0)}/R_L$  ( $\sim 10$  per cent). The large error in the absolute value of  $n$  is due largely to



the uncertainty of the absolute power level. The error in relative values of  $n$  is about 15 per cent.

The value of the power conversion gain of 0.08–0.2, obtained for sensitive rectifiers in the region of constant  $G$ , compares well with the value of  $G_{IF}$  of  $\sim 0.2$  at the  $LO$ -power of 1 mW as quoted by Torrey and Whitmer (Ref. 1, p. 33). These results indicate that the definitions (1) and (3) yield the same results also at high power levels. A curve of  $G$  vs.  $P$  which is very similar to the present curves in Fig. (2) is given by Strandberg *e.a.* in Ref. 3. According to Strandberg *e.a.*,  $G$  is proportional to  $P$  at powers below about  $10^{-5}$  W and attains a constant value of  $\sim 0.2$  already at a power of  $\sim 3 \cdot 10^{-5}$  W. In the present investigation a constant  $G$  value was obtained first at much higher powers ( $\sim 3 \cdot 10^{-4}$  W). Moreover, the constant  $S$  (Eq. (6)) as given by Strandberg *e.a.* is about  $5 \cdot 10^3$ , which is about 10 times the highest value obtained in this investigation. No explanation of these discrepancies can be given at the moment.

Assuming, that the inverse-frequency dependence of  $n$  holds up to  $\nu_0 = 60$  MHz, then  $n$ -values of 1.5–4 are obtained from relation (7) at this frequency for sensitive rectifiers at  $P = 10^{-3}$  W. These values are in good agreement with the values of 1.1–2.1 reported by Torrey and Whitmer (Ref. 1, p. 33).

According to Strandberg *e.a.* <sup>3)</sup> the noise ratio of the 1N26 rectifiers is given by:

$$n = R \frac{P^2}{\nu_0} + 1, \quad (8)$$

with  $R \simeq 10^{17} \text{ W}^{-2} \text{ Hz}$ , while by Geschwind <sup>2)</sup> and by Townes and Schawlow <sup>4)</sup> the following expressions have been given for  $n$ :

$$n = C_1 \frac{i}{\nu_0} + 1, \quad (9)$$

and

$$n = C_2 \frac{i^2}{\nu_0} + 1, \quad (10)$$

respectively. The constants  $C_1$  and  $C_2$  in the expressions (9) and (10) are:  $C_1 \simeq 2 \cdot 10^7 \text{ A}^{-1} \text{ Hz}$ ,  $C_2 \simeq 2.5 \cdot 10^{13} \text{ A}^{-2} \text{ Hz}$ ,  $i$  is the rectified  $DC$  current. Assuming, that  $i = \beta' P$  (Eq. (2)) with  $\beta' \simeq 0.3 \text{ AW}^{-1}$  (Ref. 1, p. 335) then the relations (9) and (10) become:

$$n \simeq C_1' \frac{P}{\nu_0} + 1, \quad (9a)$$

and

$$n \simeq C_1' \frac{P^2}{\nu_0} + 1, \quad (10a)$$

with,  $C_1' \simeq 6 \cdot 10^6 \text{ W}^{-1} \text{ Hz}$ , and  $C_2 \simeq 2.5 \cdot 10^{12} \text{ W}^{-2} \text{ Hz}$ .

Since  $i$  is roughly proportional to  $P$  the expressions (7) and (9a) agree with respect to the power dependence of  $n$  with the relation  $n(\cdot)i$  quoted by Torrey and Whitmer in Ref. 1, p. 34. The rather large difference between the values of the constants  $C$  and  $C'$  is probably a result of poor proofreading. The expression (10) (and (10a)) refer to "good" rectifiers for which  $\beta'$  can be close to  $1 \text{ AW}^{-1}$  and the constant  $C$  in (7) about  $2 \cdot 10^{10} \text{ W}^{-1} \text{ Hz}$ . For these rectifiers (7) and (10a) yield roughly the same values of  $n$  at  $P = 10^{-3} \text{ W}$ . However, at  $P = 10^{-6}$ , the  $n$ -values obtained from (10a) are about  $10^3$  times lower than the  $n$ -values obtained from (7). In the case of expression (8) the situation is just reversed; (8) and (7) yield roughly the same values of  $n$  at  $P = 10^{-6} \text{ W}$ , but at  $P = 10^{-3} \text{ W}$ , (8) yields  $n$ -values which are much too high (e.g.  $n \simeq 1600$  at  $\nu_0 = 60 \text{ MHz}$ ).

The  $P^2$  dependence of  $n$  in (10a) has been obtained from approximate measurements in typical spectrometer arrangements. The rectifier load impedance was in these measurements appreciably higher than the dynamic impedance of the rectifier, an arrangement which is certainly not optimum. As in the present measurements the load and rectifier impedances were matched, the difference in rectifier loading, or in some other property of the present experimental procedure and that of Townes perhaps accounts for the discrepancy between (7) and (10a)<sup>7</sup>.

For the origin of (8) Strandberg *et al.* refer to the war-time work at the University of Pennsylvania quoted by Torrey and Whitmer (Ref. 1, p. 187–197). This reference by Strandberg *et al.* is rather surprising as Torrey and Whitmer only give  $n(\cdot)V^2$ , where  $V$  is the *DC*-bias voltage in the back direction, or  $n(\cdot)I^2$ , over the range of voltages for which the back resistance of the rectifier is approximately constant.

It is generally accepted (see later) that  $n$  is proportional to  $I^2$ , where  $I$  is the exciting *DC*-current either in the forward or in the back direction. The identification of the current  $I$  with the rectified current  $i$  at microwave excitation is presumably an explanation of the  $n(\cdot)I^2(\cdot)P^2$  relation assumed by Strandberg *et al.*

According to Miller<sup>8</sup>) the noise ratio at *DC* excitation should be approximately proportional to the square of the current through the rectifier if the dynamic resistance of the latter is large compared to  $300 \Omega$ . This assumption is well satisfied for backward currents (usually,  $R > 10 \text{ k}\Omega$ ), and the present results obtained at these currents confirm the results of Miller. However, it has been found that  $n$  was roughly proportional to  $I^2$  also for the forward currents through the insensitive rectifiers, but it tended to a constant value for high forward currents through the sensitive rectifiers.

In an attempt of finding an explanation of the  $n$  vs.  $I_+$  behaviour the dynamic *DC* resistance of all investigated rectifiers was determined at various microwave power levels by the method described in Ref. 1, p. 41 and 333. The results are shown in Fig. 7, in which curve 1 is of a typical

sensitive rectifier, and curve 2 is of a typical insensitive one. Essentially the same curves (with power  $P$  replaced by the voltage  $V$  applied to the rectifier) were obtained from the static current *vs.* voltage characteristics of the rectifiers. The curve 1 in Fig. (7) has a familiar shape (Ref. 1, p. 334) and shows a rather strong variation of  $R$  with the input power to the rectifier. The dependence of  $R$  of insensitive rectifiers (curve 2, Fig. (7)) on  $P$  (and  $I_+$ ) is much less pronounced than that of sensitive rectifiers. The dynamic resistance at backward  $DC$  currents was high ( $> 5 \text{ k}\Omega$ ) for all rectifiers at the  $I_-$  values as used in the present investigation. From these results follows that  $n$  is proportional to  $I_+^2$  if  $R$  does not depend strongly on the current through the rectifier.

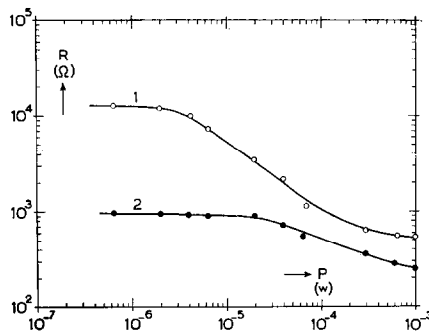


Fig. 7. The dependence of the dynamic  $DC$  resistance  $R$  on the microwave input power  $P$  to the rectifier. Curve 1 is typical for sensitive —, curve 2 for insensitive rectifiers.

The curves of figs. (5a) and (6a) showing saturation of  $\overline{V_{XT}^2(v_0)}$  and  $n$  at high forward currents through sensitive rectifiers are similar to the  $\overline{V_{XT}^2}$  *vs.*  $I_-$  curve obtained by Baker<sup>9)</sup> at high backward currents through a germanium rectifier. The author suggests that heating effects at the boundary cause changes in the dynamic  $DC$  resistance and thus lead to a decrease of the noise power. This explanation looks not probable as, (i), no saturation of  $n$  was observed at microwave excitation by powers much higher than the  $DC$  powers dissipated in the rectifiers, and, (ii), the load resistance at which the noise power was maximum at the  $DC$  excitation by a certain current was approximately equal to the dynamic  $DC$  resistance obtained from current voltage characteristics or from microwave excitation. No satisfactory explanation of the saturation phenomenon can be given at present.

*Acknowledgements.* This investigation is part of the research programme of the “Stichting voor Fundamenteel Onderzoek der Materie”, and was made possible by financial support from the “Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek”.

*Note added in proof.* Professor Strandberg informs us in a private communication that the value of the constant  $R$  in Eq. (8) was lowered to about  $1.6 \times 10^{15} \text{W}^{-2} \text{Hz}$  in a later publication (Proc. IRE **43**, (1955) 869), the decrease of the  $R$ -value reflecting the improvement of the crystal rectifiers in the past ten years. Moreover, the Eq. (8) for  $n$  seems to be based on the measurements reported in the Ph. D. thesis of H. R. Johnson (Massachusetts Institute of Technology, 1952, unpublished). In his thesis (Fig. (22)) Johnson gives four curves of  $n$  vs.  $P$ : three of them, at frequencies  $\nu_0$  of 660, 6000, and 85000 Hz, are described by Eq. (8) with the reported value of  $R$ , but the fourth one at  $\nu_0 = 50$  MHz is well described by Eq. (7) obtained in the present investigation, if  $C$  is taken approximately  $2.5 \times 10^{11} \text{W}^{-1} \text{Hz}$ . In the Johnson's measurements which yielded the  $P^2$ -dependence of  $n$  (at  $\nu_0 = 660, 6000$ , and  $85000$  Hz) the load impedance was much higher than the dynamic impedance of the rectifier, while in the measurements at 50 MHz which yielded the  $P$ -dependence, the load and rectifier impedances were matched as in the present investigation. The differences in the rectifier loading seem thus to be an explanation of the discrepancies in the power dependence of  $n$ .

Received 18-11-'59.

#### REFERENCES

- 1) Torrey, H. C. and Whitmer, C. A., Crystal Rectifiers, MIT Radiation Laboratory Series, Vol. 15, McGraw-Hill Book Company, Inc., New York (1948).
- 2) Geschwind, S., Ann. N.Y. Acad. Sci., **55** (1952) 751.
- 3) Strandberg, M. W. P., Johnson, H. R., and Eshbach, J. R., Rev. Sci. Instr. **25** (1954) 776.
- 4) Townes, C. H. and Schawlow, A. L., Microwave Spectroscopy, McGraw-Hill Book Company, Inc., New York (1955).
- 5) Nielsen, E. G., and van der Ziel, A., Rev. Sci. Instr. **25** (1954) 899.
- 6) Good, W. E., Westinghouse Research Paper 1538 (1950).
- 7) Townes, C. H., Private communication.
- 8) Miller, P. H., Proc. I.R.E. **35** (1947) 252.
- 9) Baker, D. K., J. Appl. Phys. **25** (1954) 7.