

From Galena Crystal to Semiconductor Junction: Modelling J. C. Bose's 1904 Point-Contact Detector and Its Lessons for Low-Cost Sensor Manufacturing

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Abstract- In 1904 Jagadis Chandra Bose was granted a United States patent for a detector of electrical disturbances in which a metal point pressed on a crystal of galena (lead sulphide, PbS) rectified the currents induced by electromagnetic waves. The device anticipated the semiconductor point-contact diode by several decades, but it was built before any theory of rectifying contacts existed. This paper re-examines Bose's detector with the physics of the metal-semiconductor (Schottky) barrier. A thermionic-emission model of a metal/PbS point contact is constructed from published material parameters for lead sulphide, and is used to compute the energy-band diagram, current-voltage characteristics, the transition from square-law to linear detection, the intrinsic cut-off frequency and the current responsivity as functions of contact radius, barrier height and doping. The model shows that the very high static permittivity of PbS suppresses tunnelling but enlarges the junction capacitance, so that useful response in Bose's 12–60 GHz range requires effective contact radii of about one micrometre or less, together with low barrier heights near 0.15–0.20 eV. These results give a physical explanation for the empirical search for a "sensitive spot" that characterised crystal detectors, and they translate into design rules for present-day low-cost sensors: control of effective contact area, engineering of low barriers for zero-bias operation, choice of doping to balance series resistance against tunnelling, and calibration within the square-law regime.

Keywords: J. C. Bose; galena detector; point-contact diode; Schottky barrier; lead sulphide; microwave detection;

I. INTRODUCTION

Between 1894 and 1900, working in a modest laboratory at Presidency College, Calcutta, Jagadis Chandra Bose generated and detected electromagnetic waves with wavelengths between about 2.5 cm and 5 mm, corresponding to frequencies of roughly 12–60 GHz [1]. To detect such short waves he needed receivers that were small, sensitive and reproducible. Over several years he moved from metallic coherers to contacts between metals and natural crystals, and in 1901 he applied for a United States patent on a "detector for electrical disturbances" in which the sensitive element was galena, the natural form of lead sulphide, touched by a metal point. The patent was granted in March 1904 [2]. Historians of electronics have recognised it as one of the first patents on a semiconductor device [1], [3], [4].

Bose built his detector before there was any theory that could explain it. Rectification at contacts between metals and sulphides had been reported by Braun in 1874 [5], but the physical mechanism, a potential barrier formed at the metal-semiconductor interface, was not explained until Schottky and Mott published their theories in 1938 and 1939 [6], [7]. During the Second World War, crystal detectors became central to microwave radar, and their behaviour was then studied systematically [8], [9]. Bose's own device has not, however, been analysed in the light of that later physics. This paper does so. It has two aims. The first is historical and explanatory: to ask what a modern model of a metal/PbS point contact predicts about a detector of the kind Bose described, and whether that prediction illuminates the empirical practices of early crystal-detector users. The second is practical: to extract from the model design rules that remain relevant to low-cost sensors, including printed and solution-processed devices in which lead sulphide is again an important

material [10], [11]. Section 2 summarises the historical device. Section 3 sets out the model, Section 4 gives the parameters, and Section 5 presents the results. Section 6 discusses lessons for manufacturing, Section 7 notes limitations and Section 8 concludes.

II. BOSE'S DETECTOR IN ITS SETTING

Bose's millimetre-wave apparatus consisted of a spark oscillator enclosed in a metal box, a radiating aperture, optical components such as lenses, prisms, polarisers and gratings, and a receiver connected to a galvanometer [1], [12]. Using a grating, he measured the wavelengths of his radiation directly [13]. The receiver was the critical element. Bose found that contacts between a metal and certain substances responded to electric waves without the need for mechanical tapping to restore sensitivity, unlike the filings coherers then in common use [1], [14]. Galena proved especially suitable, and his patent described a detector in which a point of metal rests on the crystal and the change in current through the contact indicates the arrival of radiation [2].

Bose's route to the crystal detector was experimental rather than theoretical. In his studies of what he called the "electric touch", he examined how contacts between different metals, and between metals and other substances, changed their conduction when exposed to electric waves, and he classified materials according to whether their resistance rose or fell [1], [12]. Galena belonged to the class of substances whose contacts responded strongly and recovered by themselves. In modern language, he had found a nonlinear junction whose conductance depends on the voltage across it, so that an oscillating field produces a net direct current. That the effect could be used to detect radiation at wavelengths of a few millimetres is remarkable, because, as Section 5 shows, the parasitic capacitance of such a contact makes high-frequency detection difficult unless the contact is very small.

The device also occupies a place in the wider history of wireless. Bondyopadhyay has argued that a mercury–iron contact detector of the type Bose described in 1899 was closely related to the device used in Marconi's transatlantic reception of December 1901, a claim that

has been debated [4]. Whatever view is taken of that episode, the galena point contact itself became the standard detector of early radio, and it was the direct ancestor of the silicon and germanium point-contact diodes developed for radar in the 1940s [3], [8].

Two features of early crystal detectors are relevant here. First, their sensitivity varied greatly from one point on the crystal surface to another, so that users searched for a "sensitive spot" by moving the whisker [3], [8]. Second, the contact had to be light; excessive pressure destroyed the effect. Both observations suggest that the effective contact area and the local properties of the interface controlled performance. Fig. 1(a) shows the arrangement schematically, and Fig. 1(b) shows the small-signal equivalent circuit used below.

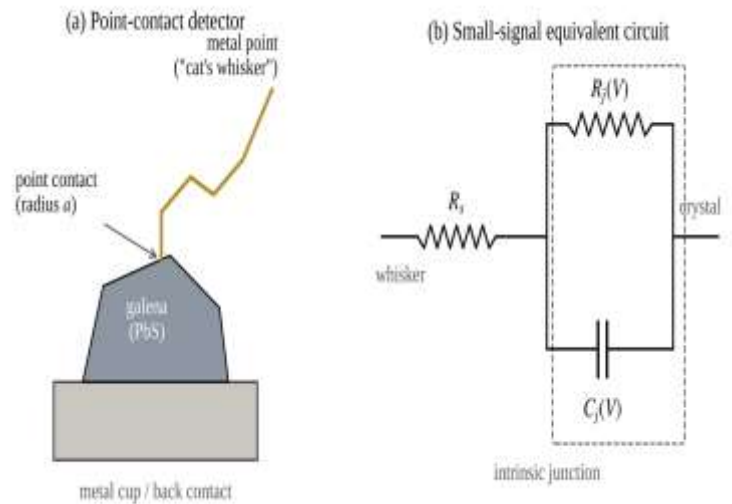


Fig. 1. Point-contact detector. (a) Schematic of a metal point resting on a galena crystal. (b) Equivalent circuit: series (spreading) resistance R_s in series with the nonlinear junction resistance R_j and depletion capacitance C_j .

III. PHYSICAL MODEL

1. Barrier and depletion region

The contact is modelled as a metal on an n-type semiconductor, forming a Schottky barrier of height ϕ_B [15], [16]. Natural galena can be either n- or p-type depending on its stoichiometry and impurities [17]; the n-type case is treated here, and the p-type case is analogous. The effective density of states in the conduction band is

$$N_c = 2 \left(\frac{2\pi m^* k_B T}{h^2} \right)^{3/2}$$

$$\eta = \frac{E_F - E_c}{k_B T} \approx \ln r + 0.35355 r - 4.95 \times 10^{-3} r^2 + 1.484 \times 10^{-4} r^3, \quad r = \frac{N_D}{N_c} \quad (2)$$

The built-in potential and the width of the depletion region at applied bias V are then

$$V_{bi} = \phi_B + \frac{k_B T}{q} \eta, \quad W = \sqrt{\frac{2\epsilon_s (V_{bi} - V - k_B T/q)}{q N_D}}$$

where $\epsilon_s = \epsilon_r \epsilon_0$ is the static permittivity [15].

2. Current transport

For a lightly or moderately doped semiconductor, transport across the barrier is dominated by thermionic emission [18]. Including the series resistance R_s , the current through a contact of radius a obeys

$$I = I_s \left[\exp \left(\frac{q(V - IR_s)}{nk_B T} \right) - 1 \right], \quad I_s = \pi a^2 A^* T^2 \exp \left(-\frac{q\phi_B}{k_B T} \right)$$

where n is the ideality factor and $A^* = 4\pi q m^* k_B^2 / h^3$ is the effective Richardson constant, equal to $120 (m^*/m_0) \text{ A cm}^{-2} \text{ K}^{-2}$ [15]. Equation (4) is solved numerically for I at each V . The importance of tunnelling is judged by the characteristic energy [19]

$$E_{00} = \frac{q\hbar}{2} \sqrt{\frac{N_D}{m^* \epsilon_s}}$$

Thermionic emission dominates when $E_{00} \ll k_B T$, thermionic-field emission when $E_{00} \approx k_B T$, and field emission when $E_{00} \gg k_B T$.

3. Rectification of a radio-frequency signal

At zero bias the small-signal junction resistance is $R_j = nk_B T / (qI_s)$. When a sinusoidal voltage of amplitude V_1 appears across the junction, and the external circuit draws no direct current, the junction develops a rectified voltage V_{dc} fixed by the condition that the

time-averaged current vanishes. For the exponential law of Eq. (4) with negligible R_s , this gives

$$V_{dc} = nV_T \ln I_0 \left(\frac{V_1}{nV_T} \right) \approx \begin{cases} \frac{V_1^2}{4nV_T}, & V_1 \ll nV_T \\ V_1 - nV_T \ln \sqrt{2\pi V_1 / nV_T}, & V_1 \gg nV_T \end{cases}$$

where $V_T = k_B T / q$ and I_0 is the modified Bessel function of order zero. The first limit is the square-law regime, in which the output is proportional to incident power; the second is the linear (peak) regime. For current-mode detection into a low-resistance galvanometer, as in Bose's apparatus, the relevant figure of merit is the current responsivity. Including the parasitic elements of Fig. 1(b), it is [20], [21]

$$\beta_i(\omega) = \frac{1}{2nV_T} \cdot \frac{1}{(1 + R_s/R_j)(1 + \omega^2 C_j^2 R_s R_j)} \quad (4)$$

with units of amperes of rectified current per watt of absorbed power. At zero bias the dominant noise is the thermal noise of the junction resistance, so the noise-equivalent power, the input power that gives a signal equal to the noise in a 1 Hz bandwidth, is [20]

$$\text{NEP} = \frac{\sqrt{4k_B T / R_j}}{\beta_i} \quad (5)$$

Smaller values of NEP indicate a more sensitive detector.

4. Parasitic elements of a point contact

The depletion capacitance of a circular contact of radius a and the spreading resistance of the semi-infinite crystal beneath it are

$$C_j = \frac{\epsilon_s \pi a^2}{W}, \quad R_s = \frac{\rho}{4a}, \quad \rho = \frac{1}{qN_D \mu_n}$$

where μ_n is the electron mobility [8], [15]. The intrinsic cut-off frequency follows as

$$f_c = \frac{1}{2\pi R_s C_j} = \frac{2W}{\pi^2 \rho \epsilon_s a}$$

Equation (10) already contains the central result of this study: the cut-off frequency of a point contact is inversely proportional to its radius. Far above the roll-off, where $\omega^2 C_j^2 R_s R_j \gg 1$ and $R_s \ll R_j$, Eqs. (4), (7) and (9) combine to give

$$\beta_i \approx \frac{1}{2nV_T \omega^2 C_j^2 R_s R_j} \propto \frac{1}{a} \exp\left(-\frac{q\phi_B}{k_B T}\right)$$

so that, at millimetre wavelengths, the response falls inversely with contact radius and exponentially with barrier height.

5. Numerical procedure and checks

The implicit current equation, Eq. (4), was solved at each bias by bracketed root finding. Equation (6) was evaluated with an exponentially scaled Bessel function to avoid overflow at large amplitudes. As a check, the rectified voltage was also obtained by direct numerical averaging of the junction current over one radio-frequency cycle, with the direct voltage adjusted until the mean current vanished.

Without series resistance the two methods agreed to better than one part in 10^9 . With the series resistance of the 1 μm contact of Section 5 ($R_s = 260 \Omega$, $R_j = 13.3 \text{ k}\Omega$) the time-domain result was lower by 3.8% at small amplitudes and by 2.0% at 100 mV, in agreement with the factor $(1 + R_s/R_j)^{-2} \approx 0.96$ implied by Eq. (7). Equation (6) is therefore an adequate description whenever $R_s \ll R_j$, which holds for all the contacts discussed below except those with the lowest barriers. The base-case band diagram was computed from the depletion approximation, in which the band bending varies quadratically with distance across the depletion region.

IV. MATERIAL PARAMETERS AND METHOD

Table 1 lists the parameters used. Room-temperature values for lead sulphide are taken from the reviews and measurements of Dalven and of Zemel and co-workers [17], [22]. Barrier heights for metal contacts on narrow-gap PbS are not well established for natural crystals, and they depend on surface preparation through Fermi-level pinning [23]. The barrier height is therefore treated as a design variable in the range 0.10–0.40 eV, which lies below the band gap of 0.41 eV. Doping is varied from 10^{16} to 10^{19} cm^{-3} , and the contact radius from 0.1 to 30 μm . All calculations were carried out in double-precision arithmetic; the implicit current equation was solved by bracketed root finding.

Table 1. Parameters of the metal/PbS point-contact model (T = 300 K).

Quantity	Symbol	Value used	Basis
Band gap (300 K)	E_g	0.41 eV	[17]
Static relative permittivity	ϵ_r	175	[17], [22]
Electron effective mass	m^*/m_0	0.10	[17]
Electron mobility	μ_n	600 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$	[17], [22]
Effective Richardson constant	A^*	12 $\text{A cm}^{-2} \text{K}^{-2}$	Eq. (4)
Effective density of states	N_c	$7.9 \times 10^{17} \text{ cm}^{-3}$	Eq. (1)
Ideality factor	n	1.1	assumed
Barrier height	ϕ_B	0.10–0.40 eV (base 0.25 eV)	design variable
Donor density	N_D	$10^{16} - 10^{19} \text{ cm}^{-3}$ (base 10^{17})	design variable
Contact radius	a	0.1–30 μm	design variable

V. RESULTS

1. Band diagram and transport regime

Fig. 2 shows the computed band diagram for the base case ($\phi_B = 0.25$ eV, $N_D = 10^{17}$ cm $^{-3}$). The Fermi level lies 0.052 eV below the conduction band in the bulk, the built-in potential is 0.198 V and the depletion width is 0.18 μ m. The resistivity is 0.10 Ω cm. From Eq. (5), E_{00} is only 1.4 meV, so that $E_{00}/k_B T = 0.05$ and transport is firmly thermionic. Even at $N_D = 10^{19}$ cm $^{-3}$, where the crystal is degenerate, $E_{00}/k_B T$ reaches only 0.54. The reason is the exceptionally large permittivity of lead sulphide, which appears in the denominator of Eq. (5). Galena therefore behaves as a thermionic rectifier over a much wider range of doping than silicon or germanium would, a property that helps to explain why rectification was readily observed in natural, impure crystals [5], [9].

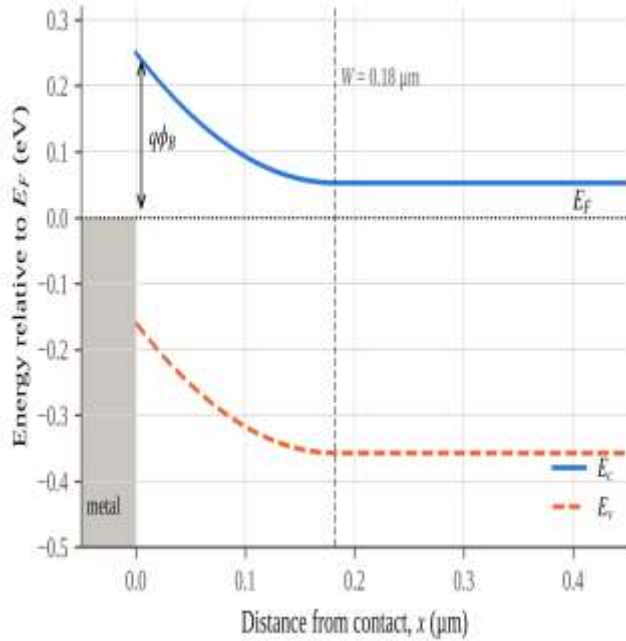


Fig. 2. Computed energy-band diagram of a metal/n-PbS contact for $\phi_B = 0.25$ eV and $N_D = 10^{17}$ cm $^{-3}$ at zero bias. The dashed vertical line marks the edge of the depletion region.

2. Current-voltage characteristics

Fig. 3 shows the current-voltage characteristics of a contact of radius 5 μ m for four barrier heights. Lower barriers give larger saturation currents and smaller

rectification ratios. At $\phi_B = 0.15$ eV the reverse current at -0.4 V exceeds 2 mA, and the device is only weakly rectifying; at $\phi_B = 0.30$ eV the reverse current falls to about 8 μ A. In forward bias all four curves bend over above about 0.2 V because of the spreading resistance of 52 Ω . The strong dependence of rectification on ϕ_B is consistent with the large point-to-point variation in sensitivity that users of crystal detectors reported [3], [8]: small local changes in surface chemistry alter the barrier and hence the characteristic.

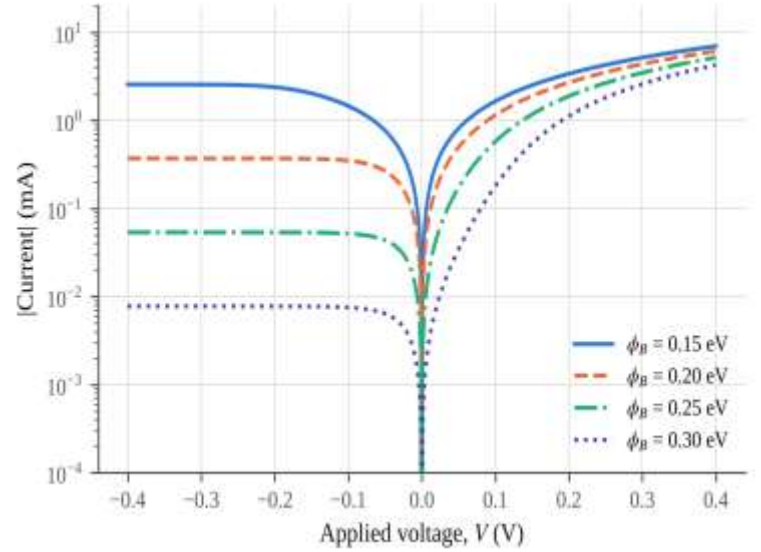


Fig. 3. Computed current-voltage characteristics of a 5 μ m metal/PbS point contact for four barrier heights ($N_D = 10^{17}$ cm $^{-3}$).

3. Square-law and linear detection

Fig. 4 compares the exact rectified voltage of Eq. (6) with its two limits. With $n = 1.1$ the square-law approximation is accurate to within 10% up to a radio-frequency amplitude of 39 mV at the junction, beyond which the response bends towards the linear limit. In the square-law regime the output is proportional to the incident power, which is what is needed for a power meter or for comparing intensities, as Bose did when measuring polarisation and reflection. At larger amplitudes the detector compresses, and comparisons of intensity become non-linear.

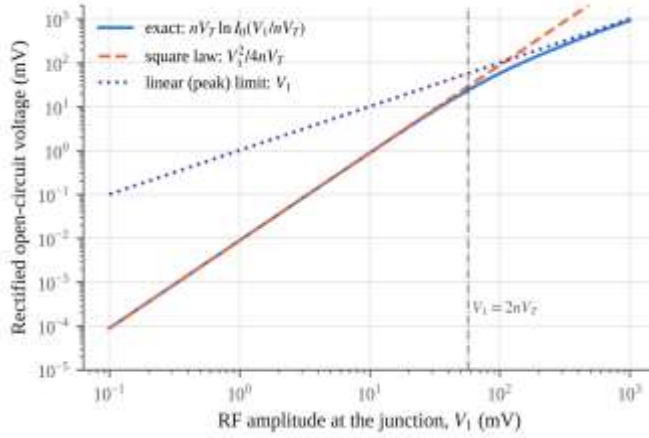


Fig. 4. Rectified open-circuit voltage as a function of the RF amplitude across the junction ($n = 1.1$, $T = 300$ K): exact result of Eq. (6) and its square-law and linear limits.

4. Frequency response and the role of contact size

Fig. 5 shows the intrinsic cut-off frequency of Eq. (10) as a function of contact radius for four doping levels. For $N_D = 10^{17} \text{ cm}^{-3}$, f_c exceeds 60 GHz only for radii below about $0.4 \mu\text{m}$ and exceeds 12 GHz only below about $2 \mu\text{m}$. A contact of $5 \mu\text{m}$ radius, which would be considered small for a hand-made whisker, has a cut-off frequency of only 4.6 GHz because its depletion capacitance, 0.67 pF , is large. Heavier doping helps, since f_c scales approximately as $N_D^{1/2}$: at 10^{19} cm^{-3} a $1 \mu\text{m}$ contact reaches 346 GHz.

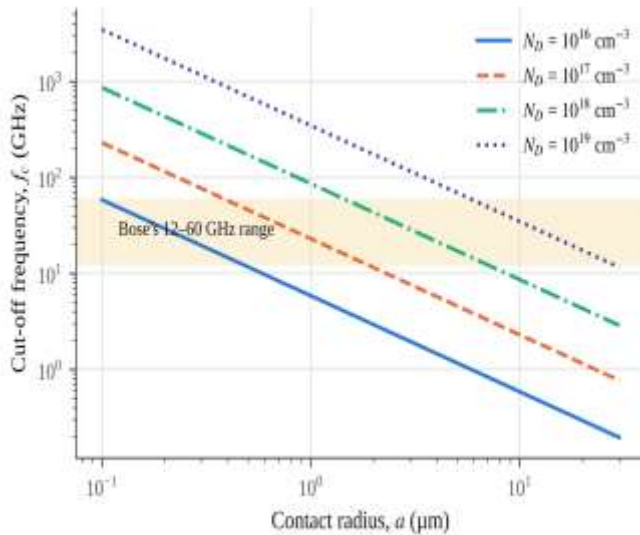


Fig. 5. Intrinsic cut-off frequency f_c of a metal/PbS point contact as a function of contact radius for four

donor densities ($\phi_B = 0.25 \text{ eV}$). The shaded band marks the 12–60 GHz range of Bose's experiments.

The cut-off frequency alone overstates the useful bandwidth, because the roll-off in Eq. (7) depends on the product $R_s R_j$ rather than on R_s^2 . Fig. 6 shows the current responsivity of contacts of radius 0.3 , 1 and $3 \mu\text{m}$. All approach the low-frequency limit $1/(2nV_T) = 17.6 \text{ A/W}$, but they fall away well below their cut-off frequencies. Table 2 lists representative values. At 60 GHz the $0.3 \mu\text{m}$ contact retains 0.17 A/W , about one hundredth of its low-frequency value, whereas the $3 \mu\text{m}$ contact retains only 0.016 A/W .

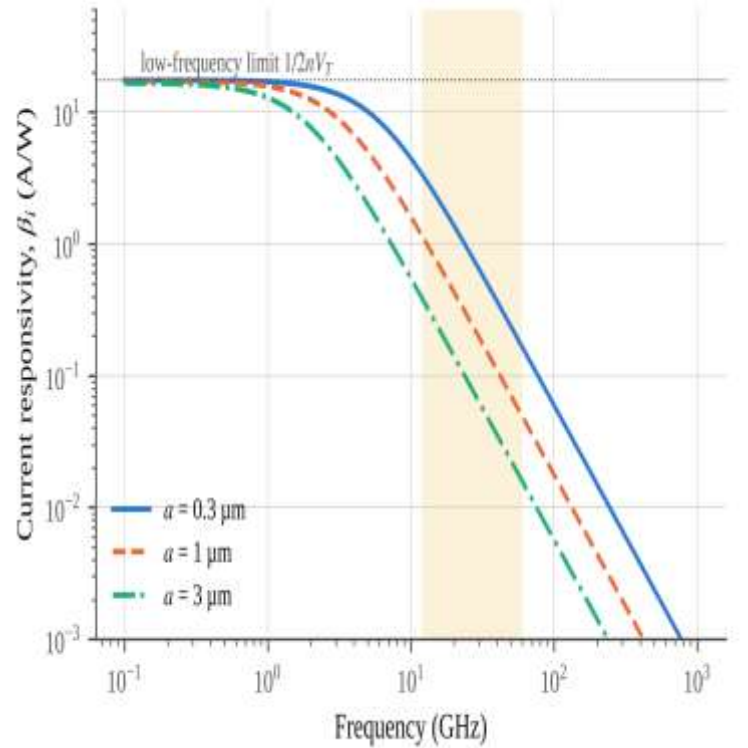


Fig. 6. Current responsivity of metal/PbS point contacts of three radii ($\phi_B = 0.25 \text{ eV}$, $N_D = 10^{17} \text{ cm}^{-3}$). The shaded band marks 12–60 GHz.

Table 2. Computed small-signal figures of merit of metal/PbS point contacts ($T = 300$ K, $n = 1.1$

a (μm)	ϕ_B (eV)	N_D (cm^{-3})	R_s (Ω)	C_j (fF)	R_j (k Ω)	f_c (GHz)	β_i at 10 GHz (A/W)	β_i at 60 GHz (A/W)
0.3	0.25	10^{17}	867	2.4	147.5	76	4.46	0.165
1.0	0.25	10^{17}	260	26.7	13.3	23	1.61	0.049
3.0	0.25	10^{17}	87	240	1.48	7.6	0.55	0.016
1.0	0.20	10^{17}	260	31.7	1.92	19	5.19	0.214
1.0	0.30	10^{17}	260	23.5	91.9	26	0.33	0.009
1.0	0.25	10^{19}	2.6	177	13.3	346	3.34	0.114

5. A design map

Fig. 7 maps the current responsivity at 60 GHz over contact radius and barrier height. Two trends stand out. Responsivity increases as the contact is made smaller, and it is greatest at low barrier heights, around 0.12–0.18 eV, where the junction resistance is low enough to limit the $\omega^2 C_j^2 R_s R_j$ term without becoming comparable to R_s . At $\phi_B = 0.30$ eV the 1 μm contact responds 24 times more weakly at 60 GHz than at $\phi_B = 0.20$ eV (Table 2).

A detector of the kind Bose used would therefore have worked best at millimetre wavelengths when the whisker happened to touch a sub-micrometre asperity on a region of low barrier height. This is a physical interpretation of the “sensitive spot”.

The noise-equivalent power of Eq. (8) gives the same ranking. At 10 GHz the 0.3 μm contact has an NEP of 7.5×10^{-14} W Hz $^{-1/2}$, the 1 μm contact 7.0×10^{-13} W Hz $^{-1/2}$ and the 3 μm contact 6.1×10^{-12} W Hz $^{-1/2}$; at 60 GHz the corresponding values are 2.0×10^{-12} , 2.3×10^{-11} and 2.1×10^{-10} W Hz $^{-1/2}$.

A spark source of the 1890s delivered pulses of considerable peak power, so even the larger contacts would have registered a signal; but the model shows why only small, well-placed contacts gave the sensitivity needed for quantitative optical experiments such as Bose’s measurements of refraction and polarisation [1], [12].

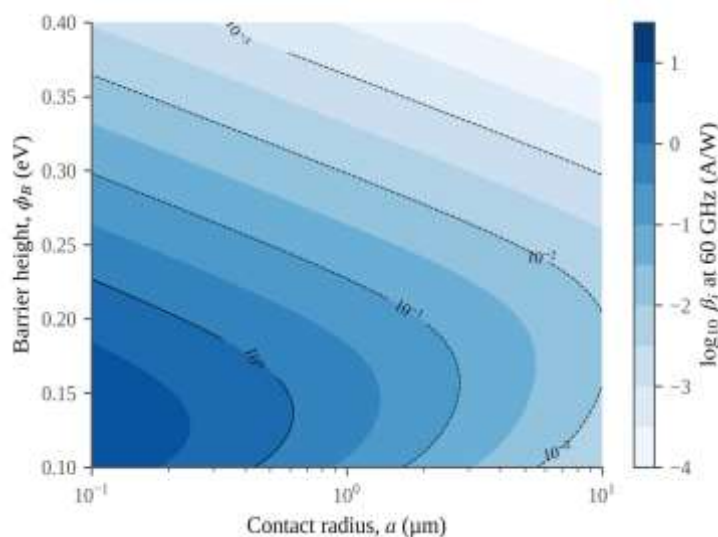


Fig. 7. Current responsivity at 60 GHz as a function of contact radius and barrier height ($N_D = 10^{17}$ cm^{-3}). Contours are labelled in A/W.

VI. LESSONS FOR LOW-COST SENSOR MANUFACTURING

The analysis yields several design rules that apply directly to inexpensive rectifying sensors, whether they are crystal detectors, printed diodes or devices made from solution-processed semiconductors.

The first rule concerns the effective contact area. Equation (10) and Fig. 5 show that bandwidth is set by the radius of the electrically active contact, not by the size of the device. For a point contact, the active area is a property of a few asperities, so it varies from one

assembly to the next and drifts with mechanical pressure. Manufacturing processes for detectors and rectifiers should therefore define the active area lithographically or by controlled overlap of printed layers, rather than leave it to mechanical contact. The 50 MHz organic rectifier of Steudel and co-workers, whose speed was limited by the same resistance–capacitance product that appears in Eq. (10), illustrates the point for printed electronics [24].

The second rule concerns the barrier height. For zero-bias detection the best barrier is low but not vanishing, because R_j must be small compared with $1/(\omega^2 C_j^2 R_s)$ yet large compared with R_s . Since barrier heights are partly pinned by interface states [23], they are controlled in practice through surface preparation and choice of contact metal. Low-cost production should therefore specify the surface treatment as tightly as the materials themselves.

Equation (11) also shows which tolerance matters most. In the roll-off regime the response varies as $1/a$, so a 30% spread in effective radius produces about a 30% spread in output. The same equation shows that a change of only 0.02 eV in barrier height, less than one $k_B T$ at room temperature, changes the response by a factor of $\exp(0.02/0.0259) \approx 2.2$. For a manufacturer of low-cost detectors, control of the interface is therefore a more demanding requirement than control of geometry, and acceptance testing should screen for barrier height, for example through the zero-bias resistance, which is proportional to $\exp(q\phi_B/k_B T)$.

The third rule concerns doping. Increasing N_D reduces the spreading resistance and raises f_c roughly as $N_D^{1/2}$, but it also narrows the depletion region and eventually allows tunnelling. In lead sulphide the large permittivity delays the onset of tunnelling (Section 5.1), which gives the designer more latitude than in materials of lower permittivity. Lead sulphide is again a material of choice for inexpensive infrared photodetectors made from colloidal quantum dots [10], [11]; in such devices the same trade-off between series resistance and junction capacitance governs speed.

The fourth rule concerns calibration. Because the square-law regime ends at a junction amplitude of a few tens of millivolts (Fig. 4), a low-cost detector used as a

power meter must either be operated below that level or be calibrated across the transition. Simple sensors are often deployed without such calibration, and the analysis shows how quickly they leave the regime in which their output is proportional to power.

Finally, the history itself carries a lesson. Bose built his detectors with local resources and treated them as instruments to be improved by careful experiment rather than as commodities [14], [25]. The modelling presented here shows that the variables he and his successors adjusted by trial and error, namely contact pressure, the choice of crystal and the selection of a sensitive spot, correspond to the physical parameters a , N_D and ϕ_B of a Schottky contact. Present-day manufacturing can control those parameters directly.

VII. LIMITATIONS

The model is deliberately simple. It treats the contact as a planar Schottky barrier with a uniform circular area, whereas a real whisker touches a rough surface at several asperities; the effective radius in this paper should be read as that of an equivalent single contact. The mobility is held constant, although it falls at high doping, and image-force lowering, minority-carrier effects and the anisotropy of natural crystals are neglected. The barrier heights are parameters rather than measured values for Bose's crystals, which do not survive in a form that allows measurement. Finally, the analysis concerns the intrinsic diode and ignores impedance matching to the incident wave, which in practice reduces the absorbed fraction of the incident power. None of these simplifications alters the main conclusions, which rest on the scaling of R_s , C_j and R_j with contact size and barrier height.

VIII. CONCLUSION

Bose's 1904 galena detector can be understood quantitatively as a metal/PbS Schottky point contact. A thermionic-emission model built from published parameters for lead sulphide shows that the material's high permittivity keeps transport thermionic even in heavily doped crystals, that detection is square-law up

to junction amplitudes of about 40 mV, and that useful current responsivity in the 12–60 GHz band requires effective contacts of about one micrometre or smaller with barrier heights near 0.15–0.20 eV. These findings explain the practical importance of light contact pressure and of the search for a sensitive spot, and they translate into design rules for low-cost sensors today: define the active area, engineer a low barrier, balance doping against tunnelling, and calibrate within the square-law range. Further work could compare these predictions with measurements on natural galena contacts and on printed PbS devices.

Declarations

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Data availability: All data needed to reproduce the results are contained in the manuscript; the parameter values and equations used for every figure are stated in the text.

Ethics approval: Not applicable.

Author contribution: The sole author conceived the study, carried out the analysis and wrote the manuscript.

REFERENCES

1. D. T. Emerson, "The work of Jagadis Chandra Bose: 100 years of mm-wave research," *IEEE Trans. Microw. Theory Techn.*, vol. 45, no. 12, pp. 2267–2273, 1997, doi: 10.1109/22.643830.
2. J. C. Bose, "Detector for electrical disturbances," U.S. Patent 755 840, Mar. 29, 1904.
3. G. L. Pearson and W. H. Brattain, "History of semiconductor research," *Proc. IRE*, vol. 43, no. 12, pp. 1794–1806, 1955, doi: 10.1109/JRPROC.1955.278042.
4. P. K. Bondyopadhyay, "Sir J. C. Bose diode detector received Marconi's first transatlantic wireless signal of December 1901 (the 'Italian Navy Coherer' scandal revisited)," *Proc. IEEE*, vol. 86, no. 1, pp. 259–285, 1998, doi: 10.1109/5.658778.
5. F. Braun, "Ueber die Stromleitung durch Schwefelmetalle," *Ann. Phys.*, vol. 229, no. 12, pp. 556–563, 1875, doi: 10.1002/andp.18752291207.
6. W. Schottky, "Halbleitertheorie der Sperrschicht," *Naturwissenschaften*, vol. 26, no. 52, p. 843, 1938, doi: 10.1007/BF01774216.
7. N. F. Mott, "The theory of crystal rectifiers," *Proc. R. Soc. Lond. A*, vol. 171, no. 944, pp. 27–38, 1939, doi: 10.1098/rspa.1939.0051.
8. H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers* (MIT Radiation Laboratory Series, vol. 15). New York, NY, USA: McGraw-Hill, 1948.
9. H. K. Henisch, *Rectifying Semi-Conductor Contacts*. Oxford, U.K.: Clarendon Press, 1957.
10. [10] G. Konstantatos et al., "Ultrasensitive solution-cast quantum dot photodetectors," *Nature*, vol. 442, no. 7099, pp. 180–183, 2006, doi: 10.1038/nature04855.
11. S. A. McDonald et al., "Solution-processed PbS quantum dot infrared photodetectors and photovoltaics," *Nat. Mater.*, vol. 4, no. 2, pp. 138–142, 2005, doi: 10.1038/nmat1299.
12. J. C. Bose, *Collected Physical Papers*. London, U.K.: Longmans, Green and Co., 1927.
13. J. C. Bose, "On the determination of the wavelength of electric radiation by a diffraction grating," *Proc. R. Soc. Lond.*, vol. 60, pp. 167–178, 1897.
14. P. Geddes, *The Life and Work of Sir Jagadis C. Bose*. London, U.K.: Longmans, Green and Co., 1920.
15. S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices*, 3rd ed. Hoboken, NJ, USA: Wiley, 2006, doi: 10.1002/0470068329.
16. E. H. Rhoderick and R. H. Williams, *Metal–Semiconductor Contacts*, 2nd ed. Oxford, U.K.: Clarendon Press, 1988.
17. R. Dalven, "A review of the semiconductor properties of PbTe, PbSe, PbS and PbO," *Infrared Phys.*, vol. 9, no. 4, pp. 141–184, 1969, doi: 10.1016/0020-0891(69)90022-0.
18. C. R. Crowell and S. M. Sze, "Current transport in metal-semiconductor barriers," *Solid-State Electron.*, vol. 9, no. 11–12, pp. 1035–1048, 1966, doi: 10.1016/0038-1101(66)90127-4.
19. [19] F. A. Padovani and R. Stratton, "Field and thermionic-field emission in Schottky barriers," *Solid-State Electron.*, vol. 9, no. 7, pp. 695–707, 1966, doi: 10.1016/0038-1101(66)90097-9.
20. A. M. Cowley and H. O. Sorensen, "Quantitative comparison of solid-state microwave detectors," *IEEE Trans. Microw. Theory Techn.*, vol. 14, no. 12,

- pp. 588–602, 1966, doi:
10.1109/TMTT.1966.1126337.
21. D. M. Pozar, *Microwave Engineering*, 4th ed. Hoboken, NJ, USA: Wiley, 2012.
 22. J. N. Zemel, J. D. Jensen, and R. B. Schoolar, "Electrical and optical properties of epitaxial films of PbS, PbSe, PbTe, and SnTe," *Phys. Rev.*, vol. 140, no. 1A, pp. A330–A342, 1965, doi: 10.1103/PhysRev.140.A330.
 23. A. M. Cowley and S. M. Sze, "Surface states and barrier height of metal-semiconductor systems," *J. Appl. Phys.*, vol. 36, no. 10, pp. 3212–3220, 1965, doi: 10.1063/1.1702952.
 24. S. Steudel et al., "50 MHz rectifier based on an organic diode," *Nat. Mater.*, vol. 4, no. 8, pp. 597–600, 2005, doi: 10.1038/nmat1434.
 25. S. Dasgupta, Jagadis Chandra Bose and the Indian Response to Western Science. New Delhi, India: Oxford Univ. Press, 1999.