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# Analysis of Physical Parameters in Electron-Beam-Irradiated Semiconductor Diodes

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## CONTENTS

# ANALYSIS OF PHYSICAL PARAMETERS IN ELECTRON-BEAM-IRRADIATED SEMICONDUCTOR DIODES

## 1. INTRODUCTION

A modulated high-energy electron beam incident on a back-biased P-N-junction diode causes a similarly modulated charge-carrier current across the depletion region of the diode. At 10 keV, an injected electron is capable of creating several thousand electron-hole pairs, and since the modulation frequency is determined by external techniques (grids, deflection plates, etc.), it is feasible that such diodes can be used potentially as high-gain, wide-bandwidth linear amplifiers (1-3). Such amplifiers work most efficiently in a class-B application, and, as will be shown here, certain advantages might be obtained in separating each push-pull component into a group of $n$ series diodes. For a given power-frequency application, the correct choice of physical parameters (e.g., diode thickness, area, impurity density) is necessary in obtaining proper functional capabilities of the device. The work described here uses a simplified model for the determination of these parameters.

The approach used is to develop the basic interaction theory between the various physical parameters, as well as beam current and supply voltage, for different power, load, and series-diode configurations. From this the power-frequency characteristics are calculated. Several design possibilities will be discussed using this approach; also other possible design variations, as well as the limitations imposed by state-of-the-art fabrication techniques, will be outlined.*

## 2. CLASS-B OPERATION

Figure 1 shows the class-B configuration with $n$ series-connected $Si$ diodes on each side. $V_S$ is the supply voltage, and $R_L$ is the load resistance. An electron beam is incident on one leg of the device (irradiating all $n$ diodes of the leg) for one half cycle and then on the other leg for the other half cycle. Each diode consists of a shallow $p^+$ region, generally a fraction of a micron in thickness, adjacent to an $n^-$ region whose thickness can vary from a few to a few hundred microns. Connected to the $n^-$ region is an $n^+$ region for providing an ohmic contact. This $Si$ diode is then mounted on an insulator, such as BeO, which in turn is coupled to a heat sink.

The electron beam penetrates through the $p^+$ region, and the electron-hole pairs are created just inside the $n^-$ region. The holes are quickly collected in the $p^+$ region while the electrons drift to the positive $n^+$ region. In the simplified model used here, it is assumed that the voltage drop across the diode is developed entirely in the $n^-$ region and that in the bulk of this region the current-density gradient is zero. In addition the following conditions are placed on the diode:

1. The maximum allowable field in the $n^-$ region is some fraction of $E_b$, the breakdown field for $Si$ ($E_b \approx 2 \times 10^5$ $V/cm$). This maximum field is taken as $E_b/2$ for a 100% safety factor in sections 3 and 4, and the effects of changing it are discussed in section 5.

*The majority of the calculations made here involve "slide rule" limits of uncertainty of a few percent rather than computer accuracy, and in many cases values have been rounded-off for simplicity. This is perfectly consistent from a practical standpoint since ambiguities in cooling rates and drift velocity etc. as well as inaccuracies in controlling parameter such as thickness and inpurity density are usually well in excess of these limits.

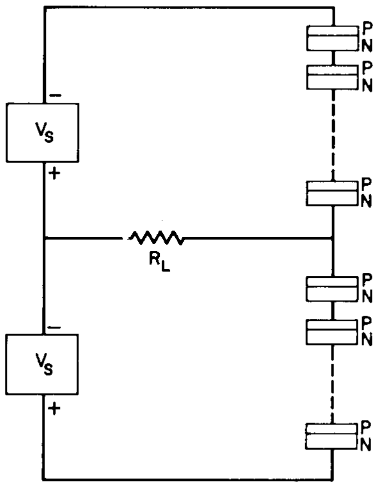


Fig. 1 — Class-B series-diode configuration for the electron-beam-irradiated semiconductor diodes

2. The minimum field across the diode (occurring when the current through it is a maximum) is given by $E_S$, the saturated-drift-velocity field for *Si* ($E_S \approx 2 \times 10^4$ *V/cm*), since operating below this field will result in a field-dependent velocity and subsequent nonlinearity. Furthermore, this field is to be made constant throughout the $n^-$ region when maximum current is being drawn. (A constant $E_S$ field at maximum current provides minimum power dissipation in the diodes.)

3. The power-dissipation capabilities in the diode are 2 kW/cm$^2$, although the effects of varying this parameter are also given in section 5.

For a sinusoidal variation in the load current $I$, the average current $\overline{I}$ and the average of the square of the current $\overline{I^2}$ are*

$$\overline{I} = \frac{I_m}{\pi}\int_0^{\pi} \sin x \, dx = \frac{2}{\pi} I_m \tag{1}$$

and

$$\overline{I^2} = \frac{I_m^2}{\pi}\int_0^{\pi} \sin^2 x \, dx = \frac{I_m^2}{2}, \tag{2}$$

where $I_m$ is the maximum current. Since $\overline{I^2}\, R_L$ is equal to $P_L$, the power in the load, then

$$I_m = \sqrt{\frac{2\, P_L}{R_L}}\,. \tag{3}$$

The supply voltage $V_S$ is equal to the maximum voltage drop across the load resistor plus the voltage drop across one string of diodes, or

*The units used here unless otherwise specified are amperes, ohms, volts and centimeters.

$$
\begin{aligned}
V_S &= I_m R_L + n E_S w \\
&= \sqrt{2 P_L R_L} + n E_S w,
\end{aligned} \tag{4}
$$

where $w$ is the diode thickness. Similarly, the maximum voltage across the diode occurs when no current is flowing through the other series of diodes. This maximum voltage $V_m$ is given by

$$
\begin{aligned}
V_m &= \frac{1}{n}\left(V_S + I_m R_L\right) \\
&= \frac{2}{n}\sqrt{2 P_L R_L} + E_S w.
\end{aligned} \tag{5}
$$

When no current flows in the diode, the field has caused all electrons to be collected, leaving only ionized donors in the $n^-$ region. This charge results in an electric-field gradient which from Poisson's equation is given by

$$
\begin{aligned}
\frac{dE}{dx} &= \frac{n_D e}{\epsilon} \\
&= 1.51 \times 10^{-7}\, n_D,
\end{aligned} \tag{6}
$$

where $e$ is the electronic charge, $\epsilon/\epsilon_0 = 12$ for $Si$, $\epsilon_0$ is $8.85 \times 10^{-14}$ farads/cm, and $n_D$ is the donor density. The maximum voltage across the diode, obtained by integrating Eq. (6), is then

$$
V_m = \frac{E_b}{2} w - 7.55 \times 10^{-8} w^2 n_D. \tag{7}
$$

Equating Eqs. (5) and (7) and solving for $w$ gives

$$
w = \frac{[(E_b/2) - E_S] - \sqrt{[(E_b/2) - E_S]^2 - \frac{60.4}{n} \times 10^{-8} \sqrt{2 P_L R_L}\, n_D}}{1.51 \times 10^{-7}\, n_D}. \tag{8}
$$

For the field in the diode to be constant when maximum current is flowing through it (condition 2), the density of electrons must equal the density of ionized donors, or $I_m/A = n_D ev$, where $v$ is the saturated drift velocity ($10^7$ cm/s for $Si$). Hence

$$
n_D = \frac{\sqrt{\frac{2 P_L}{R_L}}}{ev\, A} = \frac{\sqrt{\frac{2 P_L}{R_L}}}{1.6 \times 10^{-12}\, A}, \tag{9}
$$

where $A$ is the area per diode in cm$^2$.

The total power dissipated in all of the diodes is

$$P_{DD} = P_T - P_L$$
$$= V_S \bar{I} - \overline{I^2}\, R_L,$$

where $P_{DD}$ is the power dissipated in the diodes and $P_T$ is the total power. From Eqs. (1) – (4),

$$\begin{aligned} P_{DD} &= P_L \left(\frac{4}{\pi} - 1\right) + \frac{2n}{\pi} \sqrt{\frac{2P_L}{R_L}}\, E_S w \\ &= 0.27\, P_L + \frac{2n}{\pi} \sqrt{\frac{2P_L}{R_L}}\, E_S w. \end{aligned} \tag{10}$$

Since this power must be equal to or less than $2 \times 10^3 \times 2\, nA$, (condition 3), the diode area must satisfy the relation

$$A \geq \frac{0.27\, P_L + \dfrac{2n}{\pi} \sqrt{\dfrac{2P_L}{R_L}}\, E_S w}{4 \times 10^3\, n}, \tag{11}$$

or from Eq. (9),

$$n_D \leq \frac{4n \times 10^3 \sqrt{\dfrac{2P_L}{R_L}}}{1.6 \times 10^{-12} \left(0.27\, P_L + \dfrac{2n}{\pi} \sqrt{\dfrac{2P_L}{R_L}}\, E_S w\right)}. \tag{12}$$

## 3. MINIMUM-THICKNESS CW DESIGN

In this design the thickness of the device is made as small as possible since this decreases the transit-time limitation in frequency (which becomes important when inductances are used, as will be shown in section 6). Also the smallest usable area is desired, because this decreases the capacitance and consequently increases the bandwidth. This smallest usable area is that area which is still capable of dissipating $2 \times 10^3$ W/cm$^2$ or which can satisfy the condition for which Eqs. (11) and (12) are equalities. From Eqs. (8) and (12) it is then possible to solve for $n_D$ and $w$. However, some straightforward assumptions can be made to arrive at a simple analytical expression.

It is of interest to determine the value of the power dissipated in the diodes to calculate the efficiency and consequently to arrive at a relationship between the power dissipated in the load and that dissipated in the diodes. First, it is useful to expand the square-root term of Eq. (8) and to retain only the first three terms, since the quantity $\left[60.4 \times 10^{-8}\, n_D \sqrt{P_L R_L} / \left\{2n\, [(E_b/2) - E_S]^2\right\}\right]^2 << 1$ for typical cases. Hence

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$$w \approx \frac{\frac{2}{n}\sqrt{2 P_L R_L}}{(E_b/2) - E_S}\left[1 + \frac{7.55 \times 10^{-8}\, n_D \frac{2}{n}\sqrt{2 P_L R_L}}{[(E_b/2) - E_S]^2}\right], \tag{13}$$

where the second term in the parentheses is significantly less than unity. An estimate can be obtained using the value for $n_D \approx 3.53 \times 10^{15}\, n/\sqrt{P_L R_L}$, which will be shown to be a good approximation (Eq. (18)). Hence

$$w \approx \frac{\frac{2}{n}\sqrt{2 P_L R_L}\,[1.12]}{(E_b/2) - E_S} \tag{14}$$

Substituting Eq. (14) into Eq. (10) gives

$$P_{DD} = P_L\left\{0.27 + \frac{8}{\pi}\,\frac{E_S\,[1.12]}{[(E_b/2) - E_S]}\right\}. \tag{15}$$

The efficiency of this design is then

$$\eta = \frac{P_L}{P_L + P_{DD}}$$

$$= \frac{1}{1 + 0.27 + \frac{8}{\pi}\,\frac{E_S\,[1.12]}{[(E_b/2) - E_S]}} \tag{16}$$

$$= 50.5\%.$$

If the second term within the brackets of Eq. (13) is neglected entirely, the efficiency is raised only by 2% to the maximum value possible for the values of $E_b/2$ and $E_S$ used here. Such a design, however, uses areas much larger than the minimum area needed for dissipation and consequently reduces the bandwidth considerably. (This 2% increase in efficiency is generally not considered worth the decrease in bandwidth.)

Since the efficiency is approximately 50%, from Eq. (16) it is possible to write $P_{DD} \approx P_L$, or the power dissipated in one diode is $P_L/2n$. Since this value, divided by the area per diode, must be $2 \times 10^3$ W/cm$^2$,

$$A = \frac{P_L}{4 \times 10^3\, n}. \tag{17}$$

Substituting Eq. (17) into Eq. (9) gives

$$n_D = \frac{3.53 n \times 10^{15}}{\sqrt{P_L R_L}}, \tag{18}$$

and substituting Eq. (18) into Eq. (8) gives

$$w = \frac{0.41}{n} \sqrt{P_L R_L} \times 10^{-4} \cdot \tag{19}$$

Substituting Eq. (19) into Eqs. (4) and (5) then gives

$$V_S = 2.234 \sqrt{P_L R_L} \tag{20}$$

and

$$V_m = \frac{3.65}{n} \sqrt{P_L R_L} \cdot \tag{21}$$

Consequently Eqs. (17) — (20) give the specification for CW designs of a given power output and output-impedance requirement, and from Eq. (16) it is seen that such designs would always have an efficiency of $\approx 50\%$. The number $n$ of diodes to be used in series is left arbitrary and is a parameter which is generally to be determined from frequency requirements.

There are two factors which limit the frequency response of this type of device: (a) the transit time for a carrier to drift across the $n^-$ region, and (b) the $R_L C$ time constant formed by the product of the output impedance and the total capacitance. Figure 2 gives the equivalent circuit of the device showing the current source, the output impedance $R_L$, and the total device capacitance $C$ given by

$$C = \frac{2 \epsilon A}{n w} \cdot \tag{22}$$

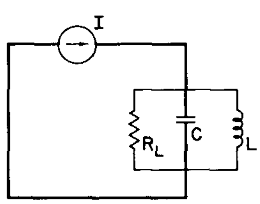


Fig. 2 — Equivalent circuit of the electron-beam-irradiated semiconductor diodes

The coil $L$ is an externally added inductance which may be used to compensate for the device capacitance in the tuned-output mode of operation, as will be discussed in more detail in section 7. (For simplicity the resistive component of the coil is neglected. Effects of added capacitance due to leads, edge effects, etc. are discussed in section 5.)

The simplest approach to solving the power-frequency relationship is to make a Laplace transformation ($t \to s$) and to solve for the case of a square-wave current pulse. Then, since this contains all equal-amplitude harmonics, the specific frequency dependence $\omega$ can be obtained by letting $s \to i\omega$. For the circuit shown in Fig. 2, the current is given by

$$i(t) = \frac{V(t)}{R_L} + C \frac{d}{dt} V(t) + \frac{1}{L} \int V(t)\, dt, \tag{23}$$

where $V(t)$ is the time-dependent voltage across the load. The Laplace transform is

$$i(s) = \frac{V(s)}{R_L} + CsV(s) + \frac{V(s)}{Ls} + CV\Big|_{t=0} + \left[\int_{-\infty}^{0} V(t)\,dt\right]_{t=0}, \tag{24}$$

where the last two terms on the right-hand side are zero. The electron beam current $I_b(t)$ incident on the $Si$ diode is given by

$$I_b(t) = Q\delta(t), \tag{25}$$

where $Q$ is the charge deposited during the current pulse and $\delta(t)$ is a delta function. The carrier current in the diode is given by

$$i(t) = \frac{NQv}{w}, \tag{26}$$

where $N$ is the number of electron-hole pairs created per incident electron. Since the current flows in the diode for the length of time $w/v$ it takes carriers to drift across it, then

$$i(s) = NQ\frac{v}{w}\int_0^{w/v} e^{-st}\,dt = \frac{NQv}{sw}(1 - e^{-sw/v}). \tag{27}$$

Substituting Eq. (27) into Eq. (24) and letting $s \to i\omega$ gives

$$V(\omega) = \frac{\dfrac{R_L NQv}{w}(1 - e^{i\omega w/v})}{i\omega - R_L C\omega^2 + (R_L/L)}. \tag{28}$$

Solving for the "dc" case or $\omega = 0$ (this corresponds to letting $L \to \infty$) gives

$$V(0) = R_L NQ. \tag{29}$$

then

$$m \equiv \frac{P(\omega)}{P(0)} = \frac{|V(\omega)|^2}{|V(0)|^2} = \frac{2(1 - \cos\theta)}{\theta^2 + \dfrac{w^2}{v^2}R_L^2 C^2(\omega^2 - \omega_0^2)^2}, \tag{30}$$

where $\theta \equiv \omega w/v$ and $\omega_0 \equiv 1/\sqrt{LC}$. From Eqs. (17), (19), and (22) and since $\epsilon = 1.06 \times 10^{-12}$ farads/cm,

$$\frac{w^2}{v^2} \approx \frac{R_L^2 C^2}{10}. \tag{31}$$

Substituting this into Eq. (30) and expanding the cosine term gives

$$1 - m = \frac{\theta^2}{12}\left(1 - \frac{\theta^2}{30} + \frac{\theta^4}{1680} \cdots\right) + 10\theta^2 m \left(1 - \frac{\omega_0^2}{\omega^2}\right)^2, \tag{32}$$

where the first term on the right-hand side arises from the transit-time limitation and the second term results from the diode capacitance and shunt inductance.

For the case where no inductance is used or $\omega_0 = 0$ (for parallel circuitry this again corresponds to $L \to \infty$), the first term on the right-hand side of Eq. (32) is negligible for $m >> 1/120$. Hence

$$\omega^2 = \frac{\dfrac{1-m}{m}}{R_L^2\, C^2}, \tag{33}$$

which indicates that the transit-time limitation can be neglected, and the frequency for this case is limited by the $R_L C$ constant of the circuit. Since $f = \omega/2\pi$ and from Eqs. (17), (19), (22), and (33),

$$f = \frac{12.3\ n \times 10^9 \sqrt{\dfrac{1}{m} - 1}}{\sqrt{P_L\ R_L}}. \tag{34}$$

A plot of power vs frequency, as obtained from Eq. (34), is given in Fig. 3 for $R_L = 50\Omega$ and various values of $P_L$ and $n$. (The dashed lines are for the case where the diode capacitance is neutralized by an inductance and the frequency limits are determined by the transit time. This latter case is discussed in section 7.)

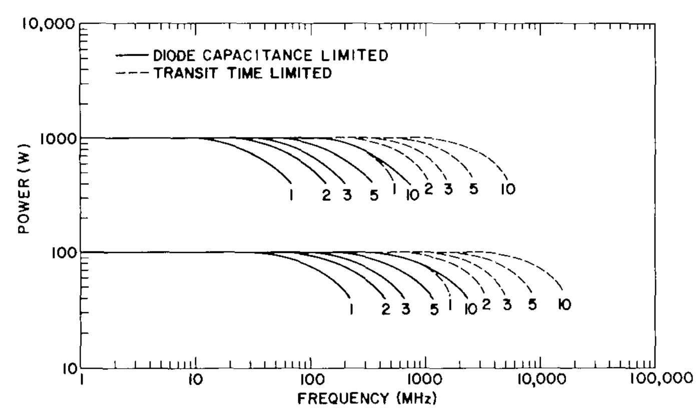


Fig. 3 — Basic interaction theory between power and frequency for the minimum-thickness design. The numbers below each curve refer to the number of series diodes in each leg of the class-B design. The dashed curves represent the transit-time limits for the various values of $n$. $R_L = 50\ \Omega$.

## 4. MINIMUM-AREA PULSED DESIGN

Since the limiting-frequency factor of the minimum-thickness (CW) design was brought about by the capacitance of the diode due to heat-dissipation considerations, it is desirable to see what the maximum *pulsed* power can be. Although the area can be decreased, since heat-dissipation problems have been removed, there is a minimum value of area usable if conditions 1 and 2 are still to be met. The smaller the area is, the larger $I_m/A$ will have to be and therefore the larger $n_D$ or $dE/dx$ (at zero current) will have to be. The maximum $dE/dx$, without going below $E_S$, requires that

$$V_m = E_S w + 2 \times 7.55 \times 10^{-8} \, w^2 n_D. \tag{35}$$

Equating this to Eq. (7) gives

$$w = \frac{(E_b/2) - E_S}{2.26 \times 10^{-7} \, n_D}. \tag{36}$$

From Eqs. (5) and (35)

$$n_D = \frac{1.87 \times 10^7 \sqrt{P_L R_L}}{n w^2}. \tag{37}$$

From Eqs. (36) and (37)

$$n_D = \frac{n[(E_b/2) - E_S]^2}{9.5 \times 10^{-7} \sqrt{P_L R_L}}$$

$$= \frac{6.74 n \times 10^{15}}{\sqrt{P_L R_L}}. \tag{38}$$

From Eqs. (37) and (38)

$$w = \frac{0.528 \times 10^{-4}}{n} \sqrt{P_L R_L}, \tag{39}$$

and from Eqs. (9) and (38)

$$A = \frac{1.31 \times 10^{-4}}{n} P_L. \tag{40}$$

From Eqs. (4) and (39)

$$V_S = 2.47 \sqrt{P_L R_L}, \tag{41}$$

and from Eqs. (5) and (39)

$$V_m = \frac{3.88}{n} \sqrt{P_L R_L}. \tag{42}$$

The efficiency $\eta = P_L/(P_L + P_{DD})$. Therefore from Eqs. (10) and (39)

$$\eta_{\text{pulsed}} = 45\%. \tag{43}$$

Since there is a minimum area usable to maintain conditions 1 and 2, this area establishes the maximum duty cycle for which the pulsed design can be used. (Any further decrease in duty cycle would not permit a wider bandwidth design, since the area cannot be made smaller, even though heat-dissipation considerations would permit it.) It is of interest to see what duty cycles could be used in the pulsed design. From Eq. (43) the average power dissipated in the diodes is $1.22P_L$ times the duty cycle ($1.22P_L$ is the peak power dissipated in the diodes). This value of average dissipated power must not exceed the value of $2 \times 10^3 A_{\text{Total}}$, as required by condition 3. Hence

$$\frac{\text{Maximum average power dissipated in diodes}}{\text{Peak power dissipated in diodes}} = \text{maximum usable duty cycle,}$$

or

$$\frac{2 \times 10^3 \times 2nA}{1.22 P_L} = 0.43. \tag{44}$$

Therefore the maximum allowed duty cycle is 43%.

The power-frequency relation is also similar to the minimum-thickness case of section 3. From Eqs. (22), (39), and (40) it is seen that

$$\frac{w^2}{v^2} \approx R_L^2 C^2. \tag{45}$$

Analogous to the treatment of Eqs. (31) and (32), the condition that the frequency relation given by Eq. (33) is valid requires that $m >> 1/12$. This still holds, since only variations in $m$ between 1/2 and 1 are considered here. Hence from Eqs. (22), (33), (39), and (40)

$$f = \frac{30.4n \times 10^9 \sqrt{\frac{1}{m} - 1}}{\sqrt{P_L R_L}}. \tag{46}$$

The power-frequency relation, as obtained from Eq. (46), shows that because of the decreased area, this design has an increased frequency response of $\approx 2.7$ over the analogous values given by Eq. 34 (and Fig. 3) for the minimum-thickness case. However, it must be remembered that $P_L$ is the pulsed power delivered to the load at no more than 43% duty cycle.

## 5. PERTURBATIONS IN $E_{max}$, $E_{min}$, COOLING RATE, AND EFFECTIVE DIODE AREA

In section 3 a minimum-thickness CW design was described, and in section 4 it was shown that increased frequency characteristics could be obtained in a minimum-area design, although this would require pulsed operation because of cooling limitations. In both of these designs the maximum field and minimum field were $E_b/2$ and $E_S$ respectively, and the cooling rate was $2 \times 10^3$ W/cm s$^2$. In this section various perturbations in these limits and the resulting new design possibilities are discussed.

If the perturbation in the maximum field and minimum field is given by

$$(E_{max} - E_{min}) = \kappa \left( \frac{E_b}{2} - E_S \right) \tag{47}$$

and

$$E_{min} = \lambda \, E_S, \tag{48}$$

then the new values of the various design parameters (designated with superscript*) are given in Table 1.

Similarly if the cooling rate is changed to $2 \times 10^3 \, \phi$ watts per active area (under the beam) and, because of lead connections, etc., the actual area is greater than the active area by a factor $\mu$, then $A^*/A = \phi^{-1}$, $n_D^*/n_D = \phi$, and $f^*/f = \phi/\mu$ for the CW minimum-thickness case, whereas the change in the maximum duty cycle for the pulsed minimum-area case is $\phi$, all other quantities remaining unchanged.

The value of $\mu$ can be estimated in terms of an effective distance $d$ around the perimeter of the diode. This distance is required for attaching connections to the diode.

Then for a circular geometry

$$\mu = 1 + 2\sqrt{\pi} \, \frac{d}{A}, \tag{49}$$

or for the minimum-thickness CW case

$$\mu \approx \frac{224 \, dn^{1/2}}{\sqrt{P_L}} \tag{50}$$

for $P_L \approx 10^3$, $n = 5$, and $d \approx 10^{-2}$, then

$$\mu \approx 1.15, \tag{51}$$

which would decrease the frequency response to a value of $\approx 0.87f$. However, the additional cooling provided by the added peripheral area might permit a slight increase in $\phi$ to partially compensate for this decrease in frequency response.

Table 1
Variations in the Design Parameters

| Parameter | Minimum-Thickness CW Case(†) | Minimum-Area Pulsed Case |
|---|---|---|
| $\frac{\eta^*}{\eta}$ | $\frac{1}{0.635 + 0.360 \frac{\lambda}{\kappa}}$ | $\frac{1}{0.57 + 0.43 \frac{\lambda}{\kappa}}$ |
| $\frac{A^*}{A}$ | $0.27 + 0.715 \frac{\lambda}{\kappa}$ | $\frac{1}{\kappa^2}$ |
| $\frac{n_D^*}{n_D}$ | $\frac{1}{0.27 + 0.715 \frac{\lambda}{\kappa}}$ | $\kappa^2$ |
| $\frac{w^*}{w}$ | $1/\kappa$ | $1/\kappa$ |
| $\frac{V_S^*}{V_S}$ | $1 - \frac{0.82\,[1-(\lambda/\kappa)]}{2.34}$ | $1 - \frac{1.06\,[1-(\lambda/\kappa)]}{2.47}$ |
| $\frac{V_m^*}{V_m}$ | $1 - \frac{0.82\,[1-(\lambda/\kappa)]}{3.65}$ | $1 - \frac{1.06\,[1-(\lambda/\kappa)]}{3.88}$ |
| $\frac{f^*}{f}$ | $\frac{1}{0.27\,\kappa + 0.73\,\lambda}$ | $\kappa$ |
| $\frac{\text{Max. Duty Cycle}^*}{\text{Max. Duty Cycle}}$ | — | $\frac{1}{0.224\,\kappa^2 + 0.776\,\lambda\,\kappa}$ |

†Because of the approximations made (e.g., Eq. (14), the values for the minimum-thickness CW case are not valid if $\kappa$ is appreciably less than unity.

## 6. MINIMUM-AREA CW DESIGN WITH HIGHER POWER PULSED CAPABILITIES

An interesting consequence of varying the limiting values of field and cooling rate is the possibility of increasing the duty cycle of the pulsed case of section 4 to 100%, thereby making this minimum-area case also applicable for CW operation. Obviously this could be accomplished if the cooling rate could be increased by a factor of $\approx 2.3$. However, this seems far above any practical cooling rate presently foreseen. On the other hand, from Table 1 it is seen that if $0.224\,\kappa^2 + 0.776\,\lambda\,\kappa \approx 0.43$, then approximately 100% duty cycle could be achieved. Hence the following relationship between $\kappa$ and $\lambda$ is required:

$$\kappa = \frac{-0.776\lambda + \sqrt{0.603\lambda^2 + 0.386}}{0.448} \tag{52}$$

Since the drift velocity does not vary too rapidly from its saturated value for fields as low as $\approx 10^4$ $V/cm$ (2), a lower practical limit of $\lambda \approx 0.5\ 1/2$ can be used where optimum linearity might not be necessary. Then from Eq. (52), $\kappa \approx 0.77$. This gives a resulting value of $E_{max}$ of $\approx 7.2 \times 10^4$ $V/cm$, which actually eases the voltage-breakdown requirement. The resulting values of the design parameters for given $P_L$, $R_L$, and $n$ are then

$$\eta = 53\%, \tag{53}$$

$$A = 2.21 \times 10^{-4} \frac{P_L}{n}, \tag{54}$$

$$n_D = \frac{4.0\, n \times 10^{15}}{\sqrt{P_L R_L}}, \tag{55}$$

$$w = \frac{0.685 \times 10^{-4} \sqrt{P_L R_L}}{n}, \tag{56}$$

$$V_S = 2.08 \sqrt{P_L R_L}, \tag{57}$$

$$V_m = \frac{3.5}{n} \sqrt{P_L R_L}, \tag{58}$$

and

$$f = \frac{23.4\, n \times 10^9}{\sqrt{P_L R_L}} \sqrt{\frac{1}{m} - 1}. \tag{59}$$

Analogous to the minimum-thickness case, a plot of power vs frequency for $R_L = 50\Omega$ and various values of $P_L$ and $n$ is given in Fig. 4 using Eq. (59). It is seen by comparing Figs. 3 and 4 (or Eqs. (34) and (59)) that this modification of $E_{max}$ and $E_{min}$ gives a frequency response increased by nearly a factor of 2 compared to the previous CW case. Furthermore, the ability to exceed the value of $E_{max}$ and still be well below the breakdown field $E_B$ makes it desirable to see what peak pulsed power can be obtained using this design.

The maximum voltage developed across the load is given by

$$I_{mP} R_L = \frac{n}{2} (E_{max} - E_{min})\, w - \frac{I_{mP}\, n w^2}{4A} \frac{1.51 \times 10^{-7}}{1.6 \times 10^{-12}}, \tag{60}$$

where $I_{mP}$ is the maximum pulsed current and the condition of space-charge compensation ($dE/dx = 0$ for maximum current) is no longer required in the calculation of the peak pulsed power.* From Eqs. (54) and (56)

$$I_{mP} = 1.58 \times 10^{-5}\, I_m\, (E_{max} - E_{min}). \tag{61}$$

*This same approach of allowing $dE/dx \neq 0$ for $I_m$ could also be applied to the minimum-thickness design. However, better power-frequency characteristics are obtained for the minimum-area design.

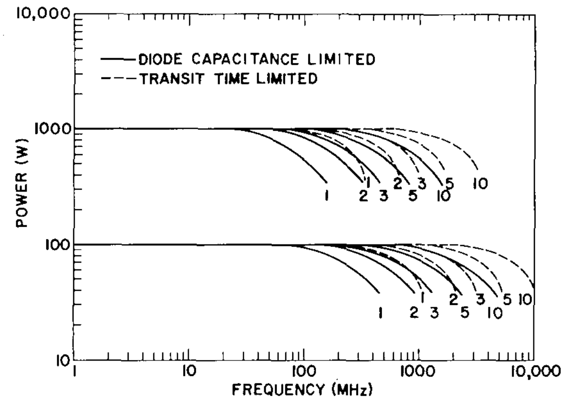


Fig. 4 — Power-frequency relationship for the minimum-area design. Notations are the same as in Fig. 3

Hence the greatest pulsed power is

$$P_P = (1.58 \times 10^{-5})^2 \, (E_{\max} - E_{\min})^2 \, P_L. \tag{62}$$

If a value of $(E_{\max} - E_{\min})$ of $\approx 10^5$ $V/cm$ is used, the maximum pulsed current $I_{mP}$ is

$$I_{mP} = 1.58 \, I_m, \tag{63}$$

and the ratio of the pulsed power to the CW power is

$$\frac{P_P}{P_L} = 2.5. \tag{64}$$

The power-supply voltage for the pulsed case must be changed to

$$V_{SP} = I_{mP} R_L + n E_{\min} w + \frac{n w^2}{2} \left\{ \frac{I_{mP}}{1.06 \times 10^{-5} A} - 1.51 \times 10^{-7} n_D \right\}, \tag{65}$$

which from Eqs. (54) — (57) and Eq. (63) gives

$$V_{SP} \simeq 1.8 \, V_S. \tag{66}$$

Since

$$\eta = \frac{P_P}{\frac{2}{\pi} V_{SP} \, I_{mP}}, \tag{67}$$

then

$$\eta \approx 47\%, \tag{68}$$

or the power dissipated in the diodes is 1.13 times the power $P_P$ dissipated in the load. Analogous to Eq. (44), the maximum duty cycle is

$$\frac{2 \times 10^3 \; 2nA}{1.13 \times 2.5 \, P_L} \simeq 0.31. \tag{69}$$

Therefore the minimum-area design can be operated in the CW mode by allowing the minimum field to decrease to $10^4$ $V/cm$ with an increase in frequency response by a factor of 2 over that for the minimum-thickness design. It can also be operated in a pulse mode by increasing the power-supply voltage to give increased power up to 2.5 times the CW power at a maximum duty cycle of ≈ 30%.

## 7. TUNED-OUTPUT MODE OF OPERATION

In all of the foregoing discussions the power-frequency characteristics of the electron-beam-irradiated semiconductor were discussed without the inclusion of an inductance to compensate for the diode capacitance. For these cases the device acts as a low-pass filter, and the frequency is limited by the diode capacitance and the load resistance. The inclusion of an inductance will give increased power at the higher frequencies with a resulting decrease in power at the lower frequencies.

At the point in frequency, $\omega_0$, where the inductance just compensates the diode capacitance, the power-frequency characteristics of the device are limited by the transit time. To calculate the decrease in power for this case when $\omega = \omega_0$, just the first term of Eq. (32) is used. Within an accuracy in $\theta$ of ≈ 3% or better for $1 \leqslant m \leqslant 1/2$, only the first two terms of the expansion in parentheses are necessary. This gives

$$\frac{\theta^2}{12} = \frac{1 \pm \sqrt{1 - 1.6\,(1 - m_0)}}{0.8}, \tag{70}$$

where $m_0$ is the value of $m$ when $\omega = \omega_0$. Remembering that $\theta \equiv 2\pi f w/v$ and that $f_0 = \omega_0/2\pi$,

$$f_0 = C \, \frac{n \times 10^{11} \sqrt{1 - (1.6\, m_0 - 0.6)^{1/2}}}{\sqrt{P_L R_L}}, \tag{71}$$

where

$$C = \begin{cases} 1.5 \text{ for the minimum-thickness case;} \\ 1.16 \text{ for the minimum-area case (pulsed);} \\ 0.90 \text{ for the minimum-area case (CW).} \end{cases} \tag{72}$$

This equation gives the transit-time limitation, and it is plotted as the dashed series of curves* in Fig. 3 and Fig. 4.

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*For the calculation of the lower values of $m_0$ in Fig. 3, and Fig. 4, the third term in the parentheses of Eq. (32) was also included.

For the case of added inductance when $\omega = \omega_0$, the first term of Eq. (32) (due to the transit-time limitation) can be considered constant for a given value of inductance, since the rapid change in $m$ with frequency due to the second term will cause the allowed variation in $m$ $(1 \leqslant m \leqslant 1/2)$ to occur in a very small region of $\theta$. Hence

$$1 - m = 1 - m_0 + \frac{\omega^2 \left(\dfrac{1-m}{m}\right)\left(1 - \dfrac{\omega_0^2}{\omega^2}\right)^2 m}{\mathring{\omega}^2}, \tag{73}$$

where $\mathring{\omega}$ is just the value of $\omega$ when no inductance is used, as given by Eq. (33). (At the lower frequencies, $m_0 \approx 1$, and the first term can be neglected entirely.) Solving for $f$ and again noting that $\mathring{f} = \mathring{\omega}/2\pi$, Eq. (73) can be rewritten as

$$f = \sqrt{f_0^2 + \frac{(\mathring{f})^2}{4}\left(\frac{m_0 - m}{1-m}\right)} \pm \frac{\mathring{f}}{2}\sqrt{\frac{m_0 - m}{1-m}}, \tag{74}$$

where $m_0$ is given by Eq. (71) or, for example, by the dashed lines of Fig. 3. It is seen that the bandwidth $\Delta f$ for a given value of $m$ is given by

$$\Delta f = \mathring{f}\sqrt{\frac{m_0 - m}{1-m}}, \tag{75}$$

which at the lower frequencies, where $m_0 \approx 1$, is just equal to $\mathring{f}$, the frequency when no inductance was added. As was shown in sections 3, 4, and 6,

$$\mathring{f} = \frac{\mathcal{D} n \times 10^9 \sqrt{\dfrac{1}{m} - 1}}{\sqrt{P_L R_L}}, \tag{76}$$

where

$$\mathcal{D} = \begin{cases} 12.33 \text{ for the minimum-thickness case;} \\ 30.4 \text{ for the minimum-area case (pulsed);} \\ 23.4 \text{ for the minimum-area case (CW).} \end{cases} \tag{77}$$

If inductances are used to maintain $m$ above 1/2 at the higher frequencies, then $f_0^2 \gg [(\mathring{f})^2/4][(m_0 - m)/(1-m)]$, and Eq. (74) can be rewritten as

$$\begin{aligned} f &\approx f_0 \pm \frac{\mathring{f}}{2}\sqrt{\frac{m_0 - m}{1-m}} \\ &\approx f_0 \pm \mathcal{D}\frac{n \times 10^9}{2 P_L R_L}\sqrt{\frac{m_0}{m} - 1}. \end{aligned} \tag{78}$$

A plot of Eq. (78) is shown in Fig. 5 for the minimum-thickness case where $P_L$ = 1 kW, $R_L$ = 50 Ω, $n$ = 5 and where inductances were added to give values of $f_0$ of 0.5, 1.0, 1.5, and 2 GHz. The dashed line again gives $m_0$ as obtained from Eq. (71) and shows the transit-time limitation of the device. (This is the case, for example, where a transmission-line-type output is used and the diode capacitance is tuned out at all frequencies.)

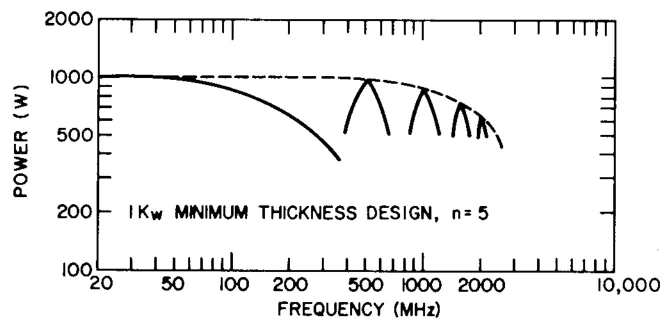


Fig. 5 — Power-frequency interaction theory from Eq. 78 for a minimum-thickness 1-kW design with a 50-Ω load and $n$ = 5. The solid curves are for inductances corresponding to $f_0$ of 0.5, 1.0, 1.5, and 2 GHz, whereas the dashed curve is again the transit-time-limited curve.

The ratio of the-3-dB bandwidth to the resonant frequency varies with frequency, as is observed from Fig. 5. From Eqs. (71), (74), and (75), this ratio is given by

$$\frac{\Delta f_{3\mathrm{dB}}}{f_0} = 0.116 \sqrt{\frac{m_0 - 0.5}{1 - (1.6\, m_0 - 0.6)^{1/2}}} \tag{79}$$

for the minimum-thickness case. It is seen from Eq. (79) that for the low-pass-filter case ($\Delta f_{3\mathrm{dB}}/f_0 \approx 1$) or the octave-bandwidth case ($\Delta f_{3\mathrm{dB}}/f_0 \approx \sqrt{2}/2$), the value of $m_0 \approx 1$. Similarly, in the transit-time-limited case, $\Delta f_{3\mathrm{dB}} = 0$ and $m_0 = 1/2$. The variation in $\Delta f_{3\mathrm{dB}}/f_0$ between these limits in $m_0$ is given in Fig. 6, which was obtained from Eq. (79). This shows, for example, that in the case where the decrease in power to the $P_L/2$ point is equally shared by the transit-time limit and that due to the untuned capacity ($m_0 = 1/\sqrt{2}$), then $\Delta f_{3\mathrm{dB}}/f_0 \approx 0.1$.

Analogous to Eq. (79), for the CW minimum-area design the constant on the right-hand side of Eq. (79) is 0.37. The values for this case are given on the right-hand ordinate of Fig. 6.

## 8. DEVICE LIMITATIONS

In section 3 a CW minimum-thickness design was described, and in section 4 a minimum-area design of increased frequency characteristics was described, but due to heat dissipation it could only be operated pulsed. In section 6 it was shown that by relaxing the lower field condition slightly, a CW minimum-area design could also be achieved. In

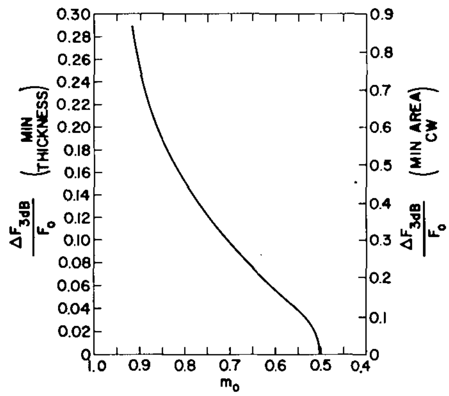


Fig. 6 — Ratio of the 3-dB bandwidth to the resonant frequency as a function of $m_0$ for the minimum-thickness case (left ordinate) and the minimum-area case (right ordinate)

this section some realistic device expectations due to limits in material parameters as well as present state-of-the-art technology are discussed for the above two CW designs.

One of the most important frequency limitations of this type of device is the minimum thickness to which the $n^-$ region can be fabricated. From Eqs. (19) and (76), for the minimum thickness case

$$f_{\mathrm{max}} = \frac{5.05 \times 10^5}{w_{\mathrm{min}}} \sqrt{\frac{1}{m} - 1}, \tag{80}$$

where $w_{\mathrm{min}}$ is the minimum thickness (cm) to which the $n^-$ region can be fabricated. At present, such a value is not much smaller than $\approx 5\ \mu$, and whereas this might decrease as fabrication techniques develop, at least presently it represents a realistic limit.* Hence using this value, from Eq. (80) it seems unlikely at this time to expect a 3-dB bandwidth ($m = 1/2$) much in excess of 1 GHz. Similarly for the CW minimum-area case, the 3-dB bandwidth limit is $\approx 3.2$ GHz. It is important to note from Eq. (80) that this value is independent of power level $P_L$, load resistance $R_L$, or the number $n$ of series diodes.

Another factor limiting the power-frequency capabilities of the device is the limit in $n$ due to electromigration in the Al surface covering the $p^+$ region. It has been shown that $10^6\ A/\mathrm{cm}^2$ is an upper limit for Al (4). Since the higher current density is experienced at the periphery of the device, the cross-sectional area at this point is $\approx 4\sqrt{A} \times 10^{-5}$, where $A$ is the area per diode of $10^{-5}$ cm is the nominal thickness used for suitable electron penetration through the Al. (The factor 4 is for a square; a factor of $2\sqrt{\pi}$ would be used for a circular geometry.) Consequently $I_m\ (4\sqrt{A} \times 10^{-5}) < 10^6$, or from Eq. (17)

$$n < \frac{R_L}{5}. \tag{81}$$

---

*Due to the finite thickness of the region in which the majority of electron-hole pairs are actually generated, the 5-$\mu$ figure is even more so a point where this simplified model would probably be no longer valid.

Hence for a 50-$\Omega$ load the maximum number of series targets that should be considered for the CW minimum-thickness case would be less than ten. Similarly, for the CW minimum-area case the number of series targets should be kept below eight. It is again noteworthy that these limits on $n$ do not depend on power level but only on the load impedance. It should also be kept in mind that these values of $n$ are the upper limits, due to electromigration problems, and that this limit might not be achieved in certain cases because of other limitations. (For example, for a design having $P_L$ = 10 W and $R_L$ = 50 $\Omega$, anything above $n$ = 2 would exceed the thickness limit, and, as will be shown in the following paragraphs, this design also will exceed the limits, due to beam power dissipation.)

Another factor which might limit $n$ is the additional power to the diode caused by the incident electron beam. Since one electron-hole pair is created for each 3.6 eV of bombarding energy (2), this additional power is $\approx nI(3.6 \times 2/\pi)$. Hence for an efficiency of $\approx$50%, the power dissipated in the diodes is

$$P_{DD} \approx P_L \left(1 + \frac{3.25}{\sqrt{P_L R_L}}\right). \tag{82}$$

The second term in the parentheses is seen to become more important at the higher values of $n$ or lower values of $P_L R_L$. If the limiting value of $n$ due to electromigration is used (Eq. (81)), then for a 1-kW, 50-$\Omega$ design for example, an additional $\approx$15% heat would have to be removed from the diodes. This could be accomplished by increasing the area by a factor of 1.15. However, this extra cooling is often provided in the various designs by the radial spreading of the heat to the spaces in between the diodes (10 for this case), and therefore no design change is probably necessary. Thus for this level of power and output impedance, electromigration is the factor which likely will limit $n$. On the other hand, since the contribution due to be beam power increases as $P_L^{-1/2}$, for low-power applications this additional heating will become the limiting factor to $n$. (At $n$ = 1, Eq. (82) further shows that the electron-beam dissipation will exceed the 15% value if a $P_L$ design is chosen below $\approx$10 W at $R_L$ = 50 $\Omega$.)

The foregoing limitations on the power-frequency characteristics can be circumvented somewhat if an inductance is used to tune out the diode capacitance and if only relatively narrow bandwidths are required. For this case the area can be made larger than the minimum value required for cooling purposes. The effect of increasing the area, as was discussed in section 3, is to increase the efficiency of the minimum-thickness design by perhaps a percent or so above the 50% value. This would not affect $w$, $V_S$, or $V_m$, although it would decrease $n_D$ inversely as $A$ is increased above the design value, the limit being somewhere in the neighborhood of $n_D \approx 10^{13}$ cm$^{-3}$. (This impurity density is presently a limit below which appreciable handling and processing problems are experienced.) From Eq. (18), this limit determines the maximum increase in area to be

$$\frac{A_{\text{max}}}{A_{\text{min thickness}}} = \frac{353}{\sqrt{P_L R_L}}. \tag{83}$$

Hence for $R_L$ = 50 $\Omega$, $P_L$ = 1 kW, and $n$ = 1, the area could be increased by a factor of $\approx$1.6 with correspondingly larger values at lower values of $\sqrt{P_L R_L}$. (Actually the area increase could exceed this somewhat with the risk of going below $E_S$.)

Another factor limiting the device performance is the rate at which the diode current can be made uniform. Since this will depend on the fabrication uniformity of the diodes, among other things, as well as on the ability to control the beam current from the electron gun, it is difficult to discuss this factor other than in qualitative terms. Suffice it is to say, however, that the voltage-current characteristics of each diode are expected to be fairly flat in the dynamic range between $V_m$ and $[V_S - I_m R_L]/n$ (the minimum voltage). Consequently, if the actual beam current incident on a diode, or the current-gain figure, is appreciably different from the design value, then that diode might actually operate in the avalanche region ($E \gtrsim E_b$) or in the cutoff region ($E \lesssim E_S$) in order to have its current equal that of the rest of the diodes. (The voltage of the other diodes will also be somewhat affected.) The resultant nonlinearity is diminished if the diodes are "leaky" (or less flat) in their characteristics or if external resistors are used in parallel with the diodes. Both of these effects, however, would reduce the efficiency of the device. At the higher frequencies, where $m$ becomes appreciably less than unity, the capacitive reactance acts as such a parallel resistance and will aid in maintaining the voltage more uniform across the diodes. In any case, the degree at which uniformity can be achieved in multidiode designs will certainly have a strong bearing on the power-frequency capabilities that can be achieved.

A factor which must also be considered in realistic power-frequency limits is the possibility of an appreciable decrease in the drift velocity with temperature. This would result in nonlinear behavior and loss of power, due to transit-time limitations at the higher frequencies. Little information is known precisely of how the drift velocity varies with temperature in the field region of $\approx 10^4$ $V/cm$, since most measurements are made at room temperature (2) or below. Specifically the usually quoted values of $E_S$ ($\approx 10^4$ $V/cm$) and saturated drift velocity ($\approx 10^7$ $cm/s$) are room-temperature values obtained by Norris (2). There are indications, however, that the drift velocity could decrease significantly at the higher temperatures that might be encountered in various designs (e. g., 125° -150°C for dissipation of 2 kW/$cm^2$, as given in condition 3 of section 2).

Other factors which will limit the power-frequency capabilities of the device are changes from the idealized designs described here that might be necessary to avoid problems such as degradation of the voltage breakdown due to the bombarding-electron-beam or cathode evaporation products. Such changes might involve elaborate beam-masking techniques or semiconductor passivation procedures which can cause $\mu$, the ratio of the actual to effective area, to become appreciably larger in magnitude than for the case described in section 5. Furthermore, apart from the voltage-breakdown problem, it might be necessary to operate the device at a lower power level, because of heat dissipation effects which in some specific designs cause $\phi$ to become significantly lower than unity. Similar to the case of uniformity, however, such problems are very subjective to the particular application for which the device is used, and it is difficult to enumerate them quantitatively. (A few quantitative guidelines for operation at reduced power levels, on the other hand, are given in section 9.)

## 9. OPERATION OF SPECIFIC DESIGNS AT VARIOUS POWER LEVELS

A CW diode design intended to operate at a specific value of $P_L$, $R_L$, and $n$ will require a certain beam current $I_b$ incident on it so that the maximum value of $I_b$ (from Eq. (3)) is given by $1/N\sqrt{2P_L/R_L}$, where $N$, as was discussed earlier, is the number of electron-hole pairs formed for each incoming electron. If it is desired to operate the device at a reduced power level by decreasing the beam current, then the power output will be decreased correspondingly as the square root of the beam current. On the other hand, if it is desired to operate at a reduced power level by decreasing the power supply voltage $V_S$, as might be required because of reverse-diode leakage or breakdown problems, then a decrease in $V_S$ must be accompanied also by a decrease in $I_b$ so that the minimum electric field does not decrease below a specified value. Since a variation in the maximum diode current will no longer allow the space-charge-compensation condition (condition 2) to be valid, the minimum field is now written as

$$E_{\min} = \frac{V_S^+}{nw} - \frac{I_m^+ R_L}{nw} - 1.51 \times 10^{-7}\, n_D \frac{w}{2} \left|1 - \frac{I_m^+}{I_m}\right|, \tag{84}$$

where the plus superscript signifies a new value of supply voltage or diode current. It is seen that if $V_S^+ = V_S$ and $I_m^+ = I_m$, then Eq. (84) reduces to Eq. (4). For the CW minimum-thickness case it is possible to write

$$\frac{V_S^+}{V_S} = \frac{I_m^+}{I_m}\left(\frac{1 \mp 0.317}{1.58}\right) + \frac{E_{\min} \times 10^{-4} \pm 1.09}{5.45} \tag{85}$$

where the upper signs are for $I_m^+ < I_m$ and the lower signs are for $I_m^+ > I_m$. Similarly, for the CW minimum-area case,

$$\frac{V_S^+}{V_S} = \frac{I_m^+}{I_m}\left(\frac{1 \mp 1}{1.48}\right) + \frac{E_{\min} \times 10^{-4} \pm 2.07}{3.07} \tag{86}$$

A plot of $V_S^+/V_S$ vs $I_b^+/I_b$ is given in Fig. 7 for various values of the minimum drift velocity $v$ encountered in the diodes. The solid lines are for the minimum-thickness case (Eq. (85)); the dashed lines are for the minimum-area case (Eq. (86)). The values of drift velocity were obtained from values of $E_{\min} \times 10^{-4}$ of 2, 1.4, 1.0, and 0.8 corresponding to $v$, $0.9v$, $0.8v$, and $0.7v$ respectively, as obtained from the empirical results of Ref. 2.

From Fig. 7 it is seen that if the minimum field value of $2 \times 10^4$ *V/cm* is to be maintained for the minimum-thickness case, then the supply voltage cannot be decreased to less than 70% of its original value without decreasing the beam current to $\approx$31% of its original value, which reduces the power output to 1/10 of its original value. However, if a drop in minimum field corresponding to 80% of the saturated drift velocity does not introduce too much distortion, then this same decrease in $V_S$ can be accomplished with a decrease in power to only $\approx$1/2 of the original value. The value of $V_S^+/V_S$ can also be increased above unity with a corresponding increase in $I_b^+/I_b$ so that the minimum field value still provides a saturated drift velocity. However, the increased voltage will cause $E_{\max}$ to rise above $E_b/2$, and the increased power will exceed the allowable limits unless pulsed conditions are used.

For the CW minimum-area case, the dashed curves show that when $I_b^+/I_b < 1$, no decrease in $V_S^+$ is permitted without dropping below the already compromised value of $0.8\,v$ ($E_{\min} = 10^4$ *V/cm*). On the other hand, operation at values of $I_b^+ > I_b$ can be

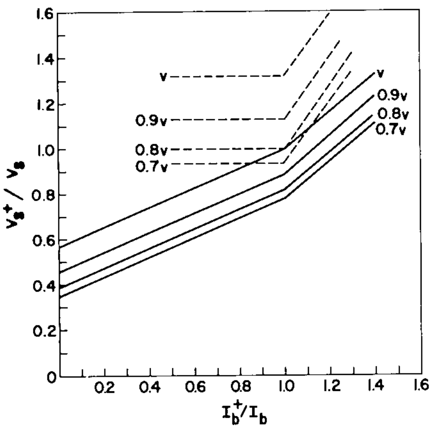


Fig. 7 — Variations in the supply voltage and beam current required to maintain various values of minimum drift velocity. The solid curves are for the minimum-thickness case; the dashed curves are for the minimum-area case.

accomplished in the pulse mode to achieve substantially higher pulsed power levels without causing the maximum field to rise appreciably above $E_b/2$. An example of this case was discussed in section 6.

## 10. SUMMARY AND CONCLUSIONS

The basic interaction theory of two design approaches is presented here, one based on minimizing the thickness and the other based on minimizing the area. The former adheres to the conditions of maximum and minimum field, as well as heat dissipation as given in section 2. Being also thinner than the second design, it is also best suited for use with an inductance, whereas the latter could be made to operate CW only by relaxing the minimum-field condition.

The lowering of $E_{min}$ for the CW minimum-area case would have the effect of perhaps introducing a slight nonlinearity* in the device, but it also provides a decrease in the maximum field required across the diode and consequently reduces the chance of device failure due to voltage breakdown. The reduced voltage across the diode required for CW operation also makes it possible to operate the device in a pulsed mode. An increase of $\approx 2.5$ in power level can by achieved by increasing the supply voltage by a factor of $\approx 1.8$. The maximum allowed duty cycle for this type of operation is $\approx 30\%$. The minimum-area design also has improved frequency characteristics, compared to the minimum-thickness design, and is best suited for the case where wide bandwidths are required and where, as was just mentioned, it might be desirable to also operate at a higher pulsed power mode. The upper frequency is limited to a 3-dB bandwidth of $\approx 3$ GHz due to diode thickness, and because of electromigration problems ($n < 10$), the power level at this frequency would be below $\approx 60$ W at $R_L = 50\ \Omega$.

The minimum-thickness design is limited to a 3-dB bandwidth of $\approx 1$ GHz and $n < 8$ with a power level at the maximum frequency of less than $\approx 100$ W (again at 50 $\Omega$). However, being thinner than the minimum-area case, this design is more applicable for tuned-output operations where inductances are used and the diode is transit-time limited.

*The exact amount of nonlinearity is difficult to calculate because of the sparsity and lack of consistency found in different empirical drift-velocity measurements.

As was shown in section 8 (Eq. (75)), when inductances are added the bandwidth does not change appreciably from the value without inductances. Consequently the 3-dB bandwidths for the case of no inductance also provide an estimate of the bandwidths for the tuned-output case.

Since the 3-dB value is often convenient to use in the specifications of various applications, it is desirable to write some of the design parameters in terms of this half-power point, i.e., $m = 1/2$. (If the specifications are given, for example, in terms of $m = 0.9$, then the corresponding 3-dB bandwidth can be obtained from Eqs. 75, 76, and 77.) Summarizing the results of sections 3, 4, 6, and 7, the resonant frequency, bandwidth, thickness, impurity density, area, supply voltage, maximum diode voltage, and efficiency are given respectively by

$$f_0 = \frac{\left\{\begin{matrix} 1.50 \\ 1.16 \\ 0.90 \end{matrix}\right\} n \times 10^{11} \sqrt{1 - (1.6\, m_0 - 0.6)^{1/2}}}{\sqrt{P_L\, R_L}}, \tag{87}$$

$$\Delta f_{3\mathrm{dB}} = \frac{\left\{\begin{matrix} 12.3 \\ 30.4 \\ 23.4 \end{matrix}\right\} n \times 10^{9} \sqrt{2\, m_0 - 1}}{\sqrt{P_L\, R_L}}, \tag{88}$$

$$w = \frac{\left\{\begin{matrix} 0.410 \\ 0.528 \\ 0.685 \end{matrix}\right\} \times 10^{-4} \sqrt{P_L\, R_L}}{n}, \tag{89}$$

$$n_D = \frac{\left\{\begin{matrix} 3.53 \\ 6.74 \\ 4.10 \end{matrix}\right\} n \times 10^{15}}{\sqrt{P_L\, R_L}}, \tag{90}$$

$$A = \frac{\left\{\begin{matrix} 2.50 \\ 1.31 \\ 2.21 \end{matrix}\right\} \times 10^{-4}\, P_L}{n}, \tag{91}$$

$$V_S = \left\{\begin{matrix} 2.23 \\ 2.47 \\ 2.08 \end{matrix}\right\} \sqrt{P_L\, R_L}, \tag{92}$$

$$V_m = \frac{\begin{Bmatrix} 3.65 \\ 3.88 \\ 3.50 \end{Bmatrix} \sqrt{P_L R_L}}{n}, \tag{93}$$

and

$$\eta = \begin{Bmatrix} 50 \\ 45 \\ 53 \end{Bmatrix} \%, \tag{94}$$

where the upper values in the brackets are for the minimum-thickness CW case of section 3, the middle values are for the minimum-area pulsed case of section 4 and the lower values are for the minimum-area CW case of section 6. Figures 8 and 9 represent Eqs. (87)-(90) in graphical form for the two CW cases (upper and lower values in brackets). The upper abscissa of Fig. 9 does, however, list the value of pulsed power when the CW minimum-area case is used in the pulsed mode.

The method of calculating the various parameters required for a given power-load requirement is to first determine $\sqrt{P_L R_L}/n$ for various *integral* values of $n$. Then from Fig. 8 or 9 (or Eqs. (87) and (88)) the integral value of $n$ is determined which best satisfies the frequency requirements. The values of $w$ and $n_D$ for these requirements can be obtained directly from the abscissa of Fig. 8 or 9 (or Eq. (89) and (90)), whereas the values of $A$ and $V_S$ are determined from Eqs. (91) and (92).

For example, if a wideband, 1-kW, CW device operating into a 50-Ω load is required having a 500-MHz 3-dB bandwidth, then the minimum-area design can be used if a slight amount of nonlinearity can be tolerated. Since the integral values of $n$ are already plotted for the 1-kW 50-Ω case, from Fig. 9 it is seen that for $n = 5$, $\Delta f_{3\mathrm{dB}} \approx 530$ MHz and for $n = 4$, $\Delta f_{3\mathrm{dB}} \approx 425$ MHz. Hence using $n = 5$, the thickness is $\simeq 30\,\mu$ and the impurity density is $\simeq 9 \times 10^{13}\, cm^{-3}$. From Eqs. (91), (92), and (93), the area per diode is $\approx 4.4\ mm^2$, the supply voltage is 465 $V$, and the maximum voltage across each diode is 155 $V$. Also, this design can be used to operate in a pulsed mode to give $\simeq 2.5$ kW with a 30% duty cycle by increasing the power-supply voltage to $\simeq 840$ $V$ and increasing the beam current by a factor of $\approx 1.6$ over the CW value.

Similarly, for example, if a 1-kW 50-Ω design is desired which will operate at a median frequency of 1 GHz with a bandwidth of 250 MHz, then from Fig. 6, $m_0 \approx 0.9$ for the minimum-thickness case. From Fig. 8 the $m_0 = 0.9$ curves show that a design having $n = 5$ adequately fulfills these requirements. Hence the proper design for this application would have five diodes in series with each diode having a thickness of $\approx 18\mu$ and an impurity density of $8 \times 10^{13}\ cm^{-3}$. Similarly from Eqs. (91)-(93), the area per diode is 5 $mm^2$, the supply voltage is 500 $V$, and the maximum voltage across each diode is 164 $V$. Since the total capacitance of the device is $\approx 28$ pF, the inductance required is $\approx 5.6$ mH. The actual characteristics of this design are illustrated in Fig. 5.

If a 1-kW, 50-Ω design were desired with octave bandwidth and whose median frequency were 3 GHz, then, since $m_0 \approx 1$ and $\Delta f_{3\mathrm{dB}} \approx 2$ GHz from Fig. 9, a minimum-area design of $n = 19$, $W = 8\,\mu$, and $n_D = 3.7 \times 10^{14}\ cm^{-3}$ would be required. This obviously violates the $n \leqslant 8$ requirement and cannot be used. On the other hand, if a 1-kW design of negligible bandwidth is desired with a 3-dB point at 10 GHz, then the

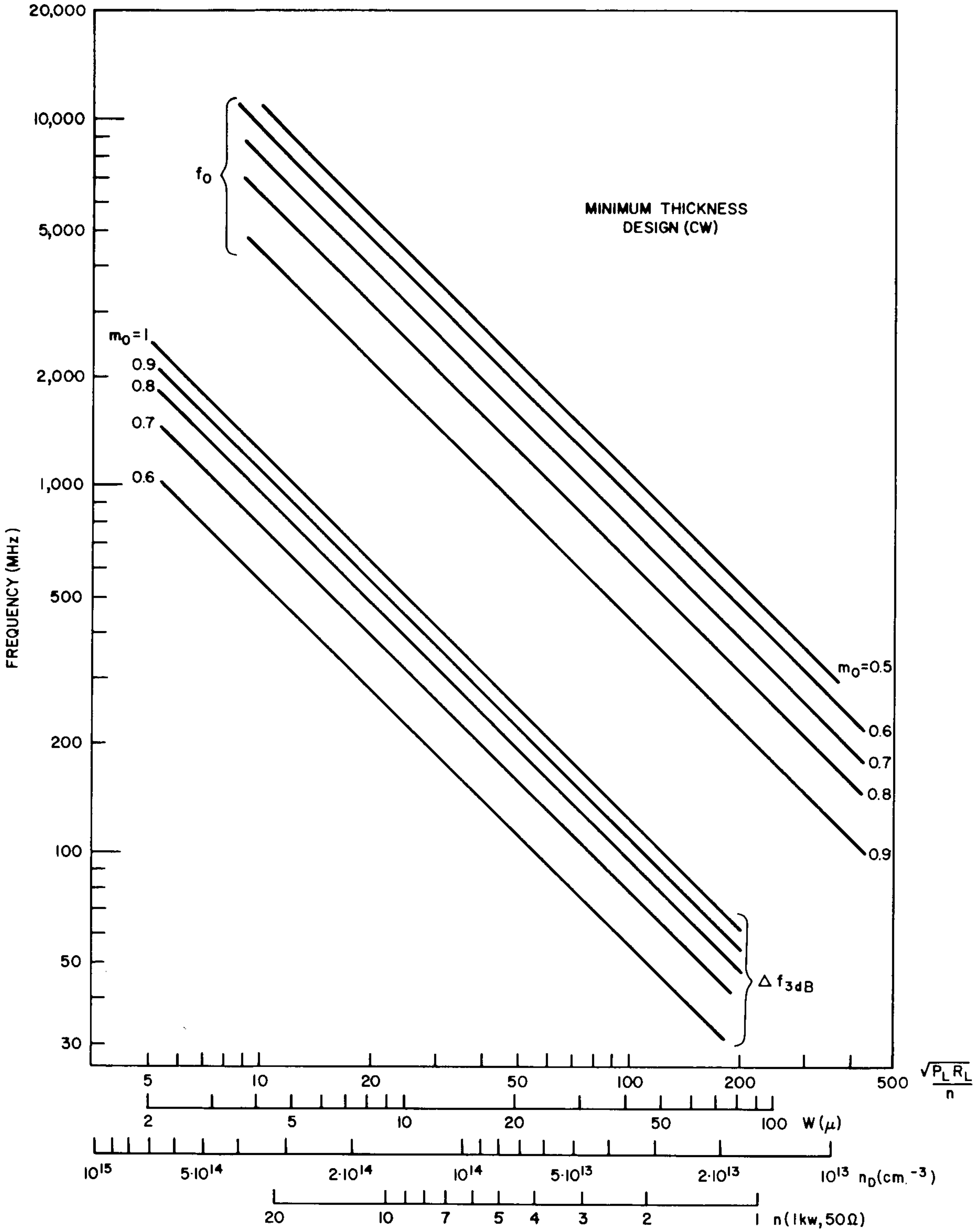


Fig. 8 — $\Delta f_{3dB}$ and $f_0$ (for various values of $m_0$) as a function of $(P_L R_L)^{1/2}/n$, $W$, and $n_D$ for the minimum-thickness case (CW)

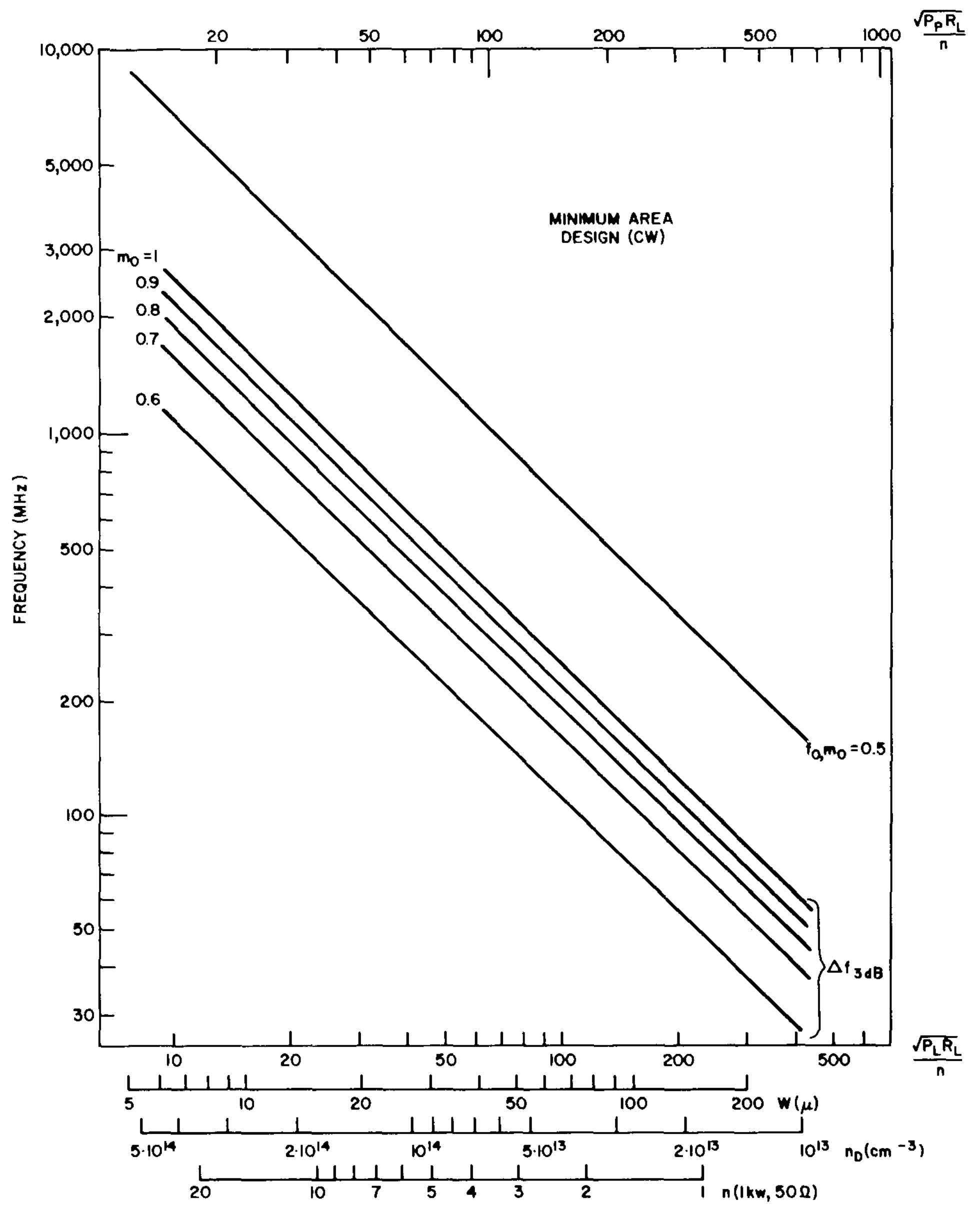


Fig. 9 — $\Delta f_{3dB}$ and $f_0$ (for various values of $m_0$) as a function of $(P_L\ R_L)^{1/2}/n$, $W$, and $n_D$ for the minimum-area case (CW). The upper abscissa is $(P_P\ R_L)^{1/2}/n$ for the pulsed mode of operation.

transit-time limit for the minimum-thickness case requires values of $n \approx 20$, $w = 4.5\ \mu$, $n_D = 3.2 \times 10^{14}\ cm^{-3}$, and $A = 1.25\ mm^2$ and an inductance of 3.16 $mH$. This again violates the maximum-$n$ condition ($n < 10$). However, since no particular bandwidth is required and since the device capacitance could be tuned out, the area could be made four times larger so that the current density through the periphery of the Al overlayer would be comparable to the case for $n = 10$. The additional capacitance would decrease the required inductance to one fourth the value, and the cooling rate would actually be capable of dissipating four times the heat generated in the diodes.

There are obviously many variations that can be employed for various specific choices of $E_{max}$, $E_{min}$, cooling rate, etc. All of these however will be subject to analogous limitations, due to electromigration, thickness, beam dissipation, uniformity, etc., as was shown in section 8. The two cases outlined here and the subsequent discussions therefore serve chiefly as a guide for the design and development of these electron-beam-irradiated semiconductor devices for various specific applications.

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13. ABSTRACT

The basic interaction theory of parameters such as thickness, impurity density, area, and external supply voltage required for various power-frequency applications is discussed for multiple electron-beam-irradiated semiconductor diodes connected in series. Two general approaches are outlined for use in CW class-B applications: (1) a minimum-thickness approach for reducing the transit-time limitations for a tuned-output high-frequency type of operation, and (2) a minimum-area approach for reducing the diode capacitance, as is desired for wide-bandwidth applications. Guidelines are also provided for changing the design conditions by altering constraints such as maximum allowed electric field, minimum allowed electric field, and heat dissipation. The power-frequency capabilities of the device are discussed in terms of present state-of-the-art fabrication limitations in controlling thickness, electromigration of the Al overlayer, uniformity of the electron beam, and electron-hole generation rate. From the results it appears that the device can be operated in the kilowatt power range for wide-bandwidth operation below 1 GHz. Above this value, however, the small device thickness and number of multiple diodes required can impose serious restrictions at these higher power densities, thereby reducing the practical power level an order of magnitude or more in a few GHz.

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