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Performance of Packaged Fast Silicon Photodetectors in a Broadband Coaxial Mount

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Transit time and avalanche buildup determine the step response of pin and avalanche photodiodes with very thin contact layers. It is calculated for packaged diodes mounted in a broadband coaxial line, and compared with measurements, yielding for a particular pin diode a rise time of 60 ps.

Das Verhalten schneller Silizium-Photodetektoren in einer breitbandigen Koaxialhalterung

Die Anstiegszeit von Pin- und Lawinenphotodetektoren mit sehr dünnen Kontaktierungsschichten wird durch Laufzeiteffekte und die Lawinenzeitkonstante bestimmt. Für gekapselte Dioden in einer breitbandigen Koaxialleitung wird die Sprungantwort berechnet und mit Messungen verglichen, was für eine spezielle Pin-Diode die Anstiegszeit 60 ps ergibt.

Progress in device technology has resulted in very thin contact layers [1] reducing the influence of carrier diffusion on the pulse response [2], [3] of silicon pin and avalanche photodiodes. Therefore the rise and fall times became ultimately limited by transit time and avalanche buildup time effects.

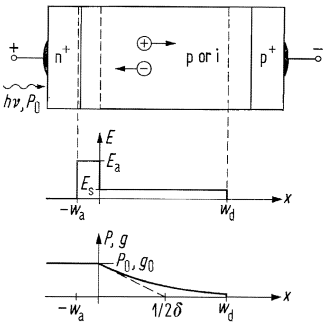

Fig. 1. Layer model of avalanche or pin photodiode, schematic of electric field strength E, light power P, and generation rate $g(x) = P_0/(h\nu A w_d)\,\mathrm{e}^{-2\delta x}$. Avalanche region: $-w_a \leqq x \leqq 0$, optical generation and drift region: $0 \leqq x \leqq w_d$.

Fig. 1 shows the assumed layer model of an avalanche (n^+pp^+) and of a pin diode structure, respectively. For an avalanche photodiode (APD) the width of the multiplication region is very small compared with the complete space-charge region because the ionization coefficients of electrons and holes increase very rapidly with the magnitude of the electric field [4]–[7] ($\sim \exp(-b/E)$, b being a constant of the order 1600 kV/cm for Si), which can be approximated by a constant E_a in an effective avalanche region of width w_a. Optical carrier generation and damping of the incident light power is to take place only in the drift region $0 \leqq x \leqq w_d$. The field is assumed to be constant and of height E_s, so that all carriers, electrons, and holes, drift with the same saturated mean drift velocity $v = 9 \cdot 10^4$ m/s. If steep edged light pulses at rather low power levels are to be observed, space-charge effects in the drift region can be neglected [7], [8]. Furthermore recombination of carriers and saturation currents are not considered.

On these assumptions the carrier concentrations of holes $p(x, t)$ and electrons $n(x, t)$ in the drift region are given by the continuity equations (1)

$$\frac{\partial p}{\partial t} + v\,\frac{\partial p}{\partial x} = g(x)\,f(t)\,, \qquad \frac{\partial n}{\partial t} - v\,\frac{\partial n}{\partial x} = g(x)\,f(t)\,,$$

with the generation rate $g(x) = P_0/(h\nu A w_d)\,\mathrm{e}^{-2\delta x} = g_0\,\mathrm{e}^{-2\delta x}$, A being the cross-section area of the device, and $f(t)$ the time function of the incident light power P_0. The solution of eq. (1) reads

$$p\,(x, t) = \frac{1}{v}\int_0^x g(x_0)\,f\left(t - \frac{x - x_0}{v}\right)\mathrm{d}x_0\,,$$
$$n\,(x, t) = \frac{1}{v}\int_x^{w_d} g(x_0)\,f\left(t + \frac{x - x_0}{v}\right)\mathrm{d}x_0\,. \qquad (2)$$

If there were no multiplication region the external current would equal the spatial average of the carrier density eq. (2) in the drift region. Let $f(t) = H(t)$ be the step function, then the step response of the external current of a pin diode can be written as

$$I'(0 \leqq t \leqq \tau_d) = \frac{q\,g_0\,A\,w_d}{2\,\delta\,w_d}\Big\{\frac{t}{\tau_d}\,(1 - \mathrm{e}^{-2\delta w_d}) + (1 + \mathrm{e}^{-2\delta w_d})/2\,\delta\,w_d - [1 + \mathrm{e}^{2\delta w_d[(2t/\tau_d)-1]}]\,\mathrm{e}^{-2\delta w_d t/\tau_d}/2\,\delta\,w_d\Big\}\,, \qquad (3)$$

$$I'(\tau_d \leqq t \leqq \infty) = \frac{q\,g_0\,A\,w_d}{2\,\delta\,w_d}\,(1 - \mathrm{e}^{-2\delta w_d})\,,$$

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q being the electronic charge, and $\tau_d = w_d/v$ the transit time.

With an APD the optically generated electron current $I_{nd}(x, t)$ enters the multiplication region and initiates the avalanche process, which gives rise to an avalanche current I_a,

$$\frac{dI_a}{dt} + \frac{I_a}{M\tau_1} = \frac{I_{nd}(x=0,t)}{\tau_1}, \qquad (4)$$

M being the bias voltage dependent multiplication factor and τ_1 the intrinsic response time in the avalanche region. If the ionization coefficients of electrons and holes were equal, τ_1 would be one half of the carrier transit time through the multiplication region of width $w_a = 2\tau_1 v$.

The multiplied secondary carriers (holes) enter the drift region and cause an external current, too.

The total external photocurrent is calculated to be

$$I(0 \leqq t \leqq \tau_d) = K_1 \left\{ K_2 \frac{t}{\tau_d} - (1 - e^{-2\delta w_d t/\tau_d})/2\,\delta w_d + 2\,\delta w_d (M\tau_1/\tau_d)^2 (1 - e^{-t/M\tau_1}) \right\} + I'(0 \leqq t \leqq \tau_d),$$

$$I(\tau_d \leqq t \leqq 2\tau_d) = K_1 \left\{ K_2 K_3 \left(\frac{t}{\tau_d} - 1\right) - 2\,\delta w_d \left(\frac{M\tau_1}{\tau_d}\right)^2 (e^{-2\delta w_d} - e^{-\tau_d/M\tau_1})(1 - e^{-(t-\tau_d)/M\tau_1}) - \right.$$
$$- K_2 \left(\frac{t}{\tau_d} - 2\right) - [e^{-2\delta w_d[(t/\tau_d)-1]} - e^{-2\delta w_d}]/2\,\delta w_d +$$
$$\left. + 2\,\delta w_d \left(\frac{M\tau_1}{\tau_d}\right)^2 (e^{-(t-\tau_d)/M\tau_1} - e^{-\tau_d/M\tau_1}) \right\} + I'(\tau_d \leqq t \leqq \infty), \qquad (5)$$

$$I(2\tau_d \leqq t \leqq \infty) = K_1 \left\{ K_2 K_3 \frac{M}{M-1} - 2\,\delta w_d \left(\frac{M\tau_1}{\tau_d}\right)^2 (e^{-2\delta w_d} - e^{-\tau_d/M\tau_1})(e^{\tau_d/M\tau_1} - 1)\, e^{-(t-\tau_d)/M\tau_1} \right\},$$

$$K_1 = \frac{q(M-1)\,A\,w_d}{2\,\delta w_d K_2}, \quad K_2 = 1 - 2\,\delta w_d M(\tau_1/\tau_d), \quad K_3 = 1 - e^{-2\delta w_d},$$

and can be represented by a current source $I_{photo}(t)$ with the special time dependence of eq. (5). The APD chip behaves, very coarsly spoken, like two low-pass filters in series, the first one having a time constant of $2\tau_d$ (in contrast to a pin diode without secondary carrier generation, where τ_d is a characteristic time), and the second one determined by a bias voltage dependent time constant $M\tau_1$. Displacement currents are taken into consideration by a barrier-layer capacitance C_{sp} in parallel with the current source. The equivalent circuit of the chip is completed by a series resistance R_s, Fig. 3a.

The chip is soldered into a ceramic S4 or pill-type package, which fits to a broadband coaxial mount, Fig. 2. The photodiode is reverse biased by a voltage source of 200 V maximum. A bias resistor of 10 kΩ limits the photocurrent, so that in conjunction with the diode-resistance-inductance (DRL) guard circuit between the inner and the outer conductor the maximum dc output voltage is less than 700 mV, well below the safe rating of sampling heads. This guard circuit introduces a negligible amplitude error, and a maximum phase error of 10° in the frequency range up to 11.5 GHz, compared to the same line without the DRL series circuit. Dynamically, the source resistance of the bias network is reduced to zero by two radial line sections, the first of which has a mica dielectric ($\varepsilon_r = 7$) with a thickness of 0.05 mm and a radial length of 3 mm; the second of which has a $BaTiO_3$ dielectric with a thickness of 1 mm, a radial length of 4 mm, and a low frequency permittivity of $\varepsilon_r = 4000$, strongly decre-

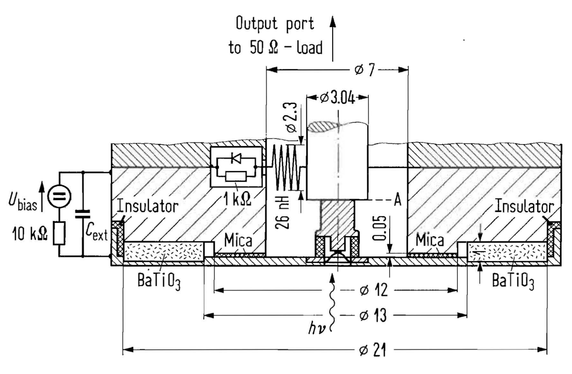

Fig. 2. Schematic of broadband coaxial mount with S4 package. Inductance produced by wrapping a thin silvered wire around M2.3 screw.

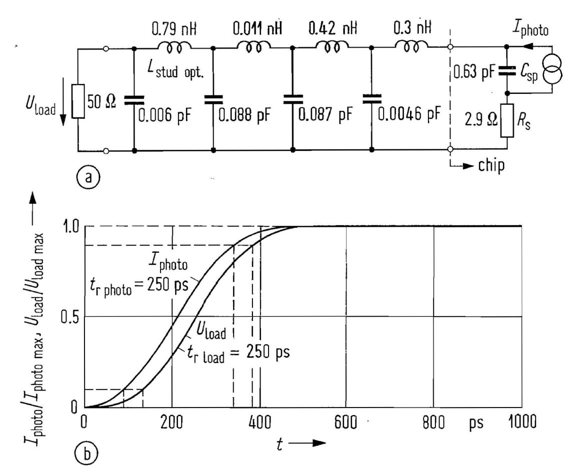

Fig. 3. (a) Equivalent circuit of mounted APD BPW 28 (S4 package).
(b) Computed step response of normalized photo current and load voltage; APD BPW 28, $w_d = 20\ \mu m$, $\tau_1 = 0.87$ ps, $w_a = 0.2\ \mu m$, $M = 38$.

asing in the GHz-range. For that reason, and because of the air gap between the mica and the $BaTiO_3$ line the mica line sees an open-circuit impedance for frequencies between 2 GHz and 18 GHz. The mica line dimensions are chosen to yield an input series resonance at 10 GHz, and an input resistance of less than 1 Ω between 2 GHz and 18 GHz. Below that range the bias resistor is effectively shorted by the $BaTiO_3$ line. It acts at very low frequencies as a lumped capacitance of 7.7 nF, which together with the load resistance of 50 Ω results in a 420 kHz low-frequency cutoff. This cutoff frequency may be easily lowered by an external capacitor C_{ext} to any desired value. Indeed, with a proper choice of the bias resistance even dc detection is possible.

For computing the equivalent-circuit [9] of the mounted and packaged chip including the inductive stud ($L_{\mathrm{stud\,opt}}$), in a frequency range up to 18 GHz, Fig. 3a, the RF-impedance in the reference plane A was measured without the DRL guard circuit. The width of the APD space-charge region (BPW 28, AEG-Telefunken) is known to be $w_{\mathrm{d}} = 20$ μm, the attenuation distance of light with $\lambda = 815$ μm in silicon is $1/(2\delta) \approx 10$ μm. The intrinsic response time of the avalanche as measured by a shot noise investigation at 2.7 GHz gave $\tau_1 = 0.87$ ps ($w_{\mathrm{a}} = 0.2$ μm), the value of which was used for further computation. In contrast to this result Kaneda and Takanashi [10] reported $\tau_1 = 0.5$ ps, while Ozeki and Watanabe [11] stated $\tau_1 = 0.85$ ps from the measurement of the dependence of the phase shift of the photocurrent on the avalanche multiplication.

Fig. 3b shows the computed normalized step response of the photocurrent source I_{photo}, eq. (5), where $M = 38$ is assumed, and the computed normalized load voltage response. The inductive stud served just as optimum compensation for fastest load voltage rise time without ringing. An increase of the multiplication factor to $M = 126$ leads to similar curves with $t_{\mathrm{r\,photo}} = t_{\mathrm{r\,load}} = 340$ ps. An APD produced with $w_{\mathrm{d}} = 8$ μm would show a like behaviour, but for $M = 38$ a rise time of photocurrent and load voltage of about $t_{\mathrm{r\,photo}} = t_{\mathrm{r\,load}} = 125$ ps should be observed.

With pin diodes ($w_{\mathrm{d}} = 8$ μm, $C_{\mathrm{sp}} = 1.1$ pF, BPX special, Siemens) optimum rise times of $t_{\mathrm{r\,load}} = 125$ ps are to be expected, while the photocurrent rises with $t_{\mathrm{r\,photo}} = 60$ ps. Pin diodes with smaller light sensitive area ($w_{\mathrm{d}} = 8$ μm, $C_{\mathrm{sp}} = 0.2$ pF) are computed to have the fastest load voltage rise time of $t_{\mathrm{r\,load}} = t_{\mathrm{r\,photo}} = 60$ ps when optimally compensated, as is supported by experiments [1].

Measurements of the step response of photodiodes are rather difficult, because a light source with a clean step output of 100 ps rise time is not easily available. On the other hand steep pulses with widths in the order of the rise time can be obtained from a GaAs injection laser with strong spiking. The drawback is that no stationary state can be seen from the output of the detector under test and therefore no meaningful rise time can be defined.

To overcome this trouble a fast reference pin diode [1] was used to monitor the spiking light signal. This detector had the above mentioned calculated rise time of 60 ps and was assumed to indicate the true light signal. If the detector system rise time was 60 ps indeed, a maximum error of 11% would result in measuring the shortest light rise time of 130 ps.

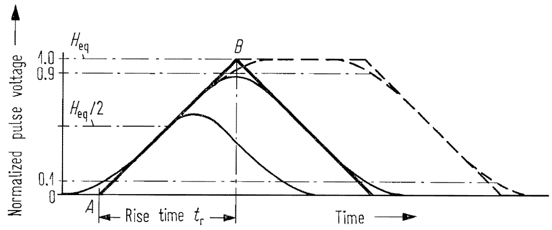

Fig. 4. Schematic of detector output pulse voltage, normalized to the equivalent stationary value H_{eq}; ——— measured, ----- equivalenced pulse.

From Fig. 4 the rise time t_{r} of the output voltage pulse of the detector was defined by the projection of the line segment AB on the time axis. This line segment is constructed as tangent in the point of inflection of the pulse, extending from the intersection point with the time axis to twice the voltage $H_{\mathrm{eq}}/2$ in the point of inflection. Thereby the equivalent pulse height H_{eq} is defined, which would be reached for a longer incident light pulse.

With the available short light pulses the pin and APD detectors under test will not yield their maximum output voltage, which corresponds to the applied maximum input light power, measured by the reference voltage H_{eq}. But it is known, however, by calibration with a pulse of 10 ns width, what stationary-state amplitude would be reached by the test detector, viz. $H_{\mathrm{eq\,test}}$. Therefore the maximum slope m of the test detector output voltage is measured and its rise time calculated from $t'_{\mathrm{r}} = H_{\mathrm{eq\,test}}/m$. Because of the finite light rise time t_{rL} the rise time of the test detector is corrected to be

$$t_{\mathrm{r\,load}} = \sqrt{t'^2_{\mathrm{r}} - t^2_{\mathrm{rL}}},$$

with an estimated accuracy of 20%.

By this technique $t_{\mathrm{r\,load}} = 135$ ps was measured for the pin diode BPX special, confirming the theoretical result of 125 ps. Therefore one can be rather confident about the calculated 60 ps rise time of the reference detector, which has a similar structure.

For the APD BPW 28 following data were measured, depending on the multiplication factor M: $t_{\mathrm{r\,load}}(M = 7) = 270$ ps, $t_{\mathrm{r\,load}}(M = 14) = 240$ ps, $t_{\mathrm{r\,load}}(M = 38) = 305$ ps, $t_{\mathrm{r\,load}}(M = 51) = 345$ ps, $t_{\mathrm{r\,load}}(M = 126) = 355$ ps, $t_{\mathrm{r\,load}}(M = 256) = 460$ ps. The calculated values for $M = 38$ and $M = 126$ are 250 ps and 340 ps, and correspond the measurements with an error of 18% and 1.4%, respectively. Most significant is the increase of the rise time with the multiplication factor M, when the term $M\tau_1$ in eq. (5) becomes dominating.

Acknowledgements

The author would like to thank Dr. S. Maslowski (AEG-Telefunken), Dr. J. Müller (Universität Braunschweig), and Dr. D. Schicketanz (Siemens) for providing the photodiodes. Financial support of the Deutsche Forschungsgemeinschaft is gratefully acknowledged. The numerical calculations were carried out on a UNIVAC-1108 computer at the Rechenzentrum, Universität Karlsruhe.

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Erratum

W. Freude, Performance of Packaged Fast Silicon Photodetectors in a Broadband Coaxial Mount (AEÜ **31** [1977], 167—170).

Page 167: In the caption to Fig. 1 and in the first line following eq. (1) the equation for $g(x)$ should read

$$g(x) = 2\,\delta w_\mathrm{d}\,P_0/(h\nu\,A\,w_\mathrm{d})\,\mathrm{e}^{-2\delta x}.$$

Page 168: Eq. (5), last two lines, should read

$$I(2\,\tau_\mathrm{d} \leqq t \leqq \infty) = K_1\left\{K_2 K_3 \frac{M}{M-1} - 2\,\delta w_\mathrm{d}\left(\frac{M\tau_1}{\tau_\mathrm{d}}\right)^2 (\mathrm{e}^{-2\delta w_\mathrm{d}} - \mathrm{e}^{-\tau_\mathrm{d}/M\tau_1})\,(\mathrm{e}^{\tau_\mathrm{d}/M\tau_1} - 1)\,\mathrm{e}^{-(t-\tau_\mathrm{d})/M\tau_1}\right\},$$

$$K_1 = \frac{q\,(M-1)\,g_0\,A\,w_\mathrm{d}}{2\,\delta w_\mathrm{d}\,K_2}, \quad K_2 = 1 - 2\,\delta w_\mathrm{d}\,M\,(\tau_1/\tau_\mathrm{d}), \quad K_3 = 1 - \mathrm{e}^{-2\delta w_\mathrm{d}}.$$

The other relations of eq. (5) remain unchanged.