Characteristics of an Area-Variable Varactor Diode

Dong-Wook Kim, Jae-Jin Lee, Young-Se Kwon, and Song-Cheol Hong

Abstract—**Photoresponses and microwave characteristics of an area-variable varactor diode are investigated in the frequency range of 1–7 GHz. The on/off ratio of the capacitance as large as 18.5 at 1 GHz is demonstrated and it is shown that the ratio strongly depends upon the access resistance between the cathode and the floating contacts. The capacitance of the diode is significantly altered by optical illuminations. The change increases nonlinearly with the input light power and the maximum value of 450% is achieved at 1 GHz with 1045 nW light power. These microwave and optical characteristics are described with a simple equivalent circuit model.**

I. Introduction

VARIOUS varactor diodes have been extensively used in microwave applications, which include bandpass filter [1], [2], phase shifter [3], voltage-controlled oscillator [4], [5], mixer [6], nonlinear transmission line [7], [8], and frequency multiplier [9]–[14]. The bandpass filter and the phase shifter require a large capacitance change to obtain wide bandwidth performance. This is because these circuits generally use a varactor diode as an element of an LC resonant circuit and its resonance frequency is inversely proportional to the square root of capacitance value. In the voltage-controlled oscillator applications, the applied bias voltage determines oscillation frequency through capacitance variation. Therefore, the voltage-controlled oscillator requires proper capacitance–voltage characteristics for linear frequency tuning as well as a large capacitance change for a large bandwidth. On the other hand, highly nonlinear capacitance characteristics are important in such applications as mixer, nonlinear transmission line, and frequency multiplier because these circuits utilize harmonics generated through nonlinear impedance.

All the devices previously reported have common limitations that the capacitance ratios, $C_{\max}/C_{\min}$, of them fabricated on a single wafer should be the same and the capacitance–voltage characteristics should be determined by an epitaxial layer. To overcome these limitations, we proposed a novel area-variable varactor diode [15], whose capacitance characteristics were determined mainly by layout patterns. The proposed diode can increase the capacitance ratio to larger value than other varactors and have various ratios on the same wafer. We also find that the capacitance of the structure is very sensitive to external photo-illuminations. This property can be utilized in optically controlled circuits such as optically controlled oscillators and mixers [16].

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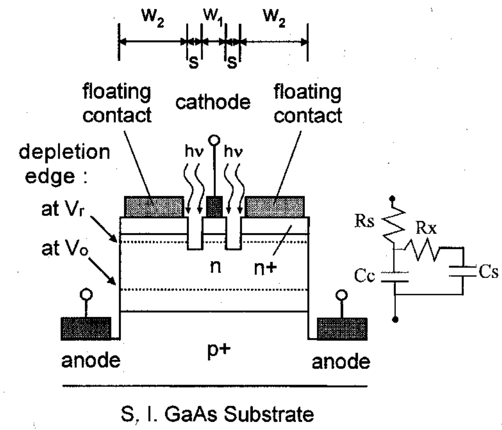

Fig. 1. The cross-sectional view of the area-variable varactor diode and its equivalent circuit (V_o: zero bias voltage, V_r: fully reversed bias voltage).

In this paper, we present the microwave characteristics and photoresponses of an area-variable varactor diode. The operation of the diode is explained with an equivalent circuit model. In Section II, the operation and the structure of the area-variable varactor diode are presented. The microwave characteristics of the diode are given in Section III. The photoresponses of the diode are given in Section IV. Finally, in Section V, conclusions are drawn.

II. The Area Variable Varactor Diode

The operation of the area-variable varactor diode is based on the change of effective depletion area. Fig. 1 shows the cross sectional view of the diode and its equivalent circuit, which consists of anode, cathode and floating metal contacts separated from the cathode by spacing, "S." When the bias voltage is zero, the effective depletion area is large as shown in Fig. 1. If it is fully reverse-biased, the effective depletion area becomes very small due to the fact that the depletion regions under the floating contacts are isolated from the depletion region under the cathode. This leads to a large on/off capacitance ratio, $C_{\max}/C_{\min}$, which is proportional to area ratio, $(2W_2 + 2S + W_1)/W_1$. Therefore, the capacitance ratio of the area-variable varactor can be determined by the layout which includes the widths of the cathode, the floating contacts and the spacings between the cathode and floating contacts.

The area-variable varactor diode has been fabricated in the following sequence. The process flow is shown in Fig. 2. First, the active region is isolated by a solution of 1 : 1 : 100 NH_4OH : H_2O_2 : H_2O. Then, dielectric film (Si_xN or

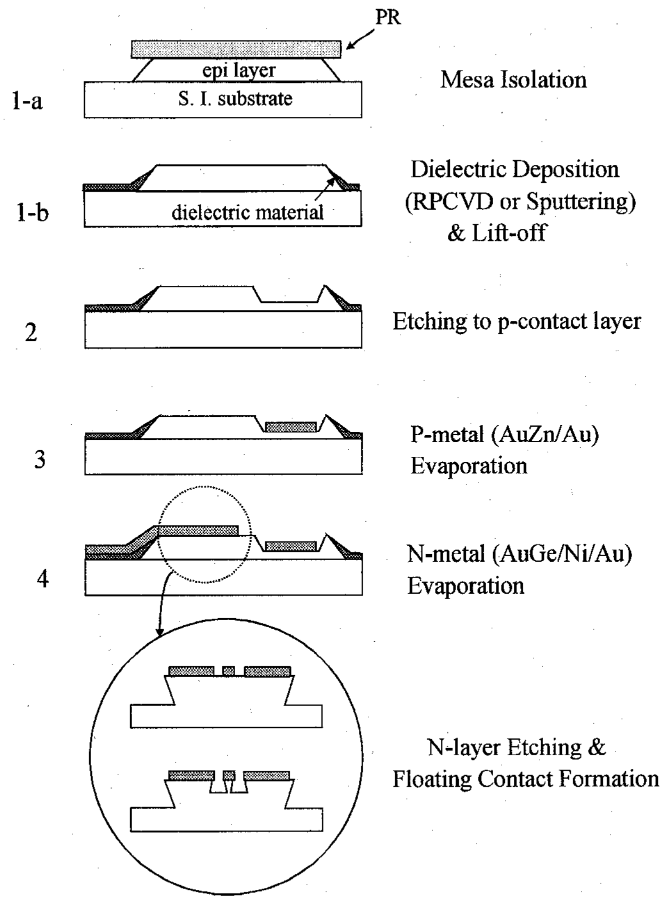

Fig. 2. The process flow of the area-variable varactor diode.

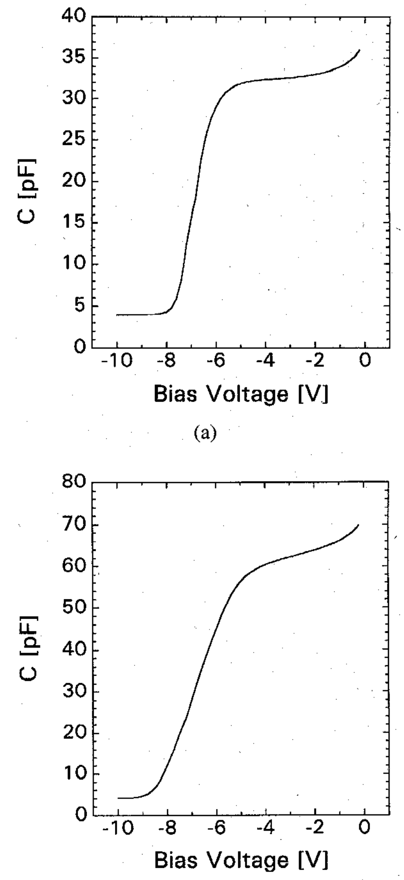

Fig. 3 The large-area quasistatic C-V characteristics of the area-variable varactor diodes (measurement frequency = 1 MHz) (a) area ratio = 9 : 1 and (b) area ratio = 16 : 1.

SiO_2) is deposited by a sputtering machine or the Remote Plasma Chemical Vapor Deposition (RPCVD) system and lift-off process is performed consecutively. To reduce parasitic capacitance and resistance, an air bridge process or a trench isolation can be used. Second, the n active layer is etched to a p^+ layer and a p ohmic metal (AuZn/Au) is evaporated. Third, the n ohmic metal (AuGe/Ni/Au) is evaporated and n and p metals are alloyed simultaneously by the Rapid Thermal Annealing (RTA) system. Fourth, the n active layer is slightly etched to separate the cathode from the floating contacts. Finally, Au electroplating is performed to reduce the resistance of the metallizations. This process is compatible with conventional MMIC process except for the p ohmic metal evaporation.

Fig. 3 shows C–V characteristics of the area-variable varactor diode at 1 MHz. The measured diodes have 9 : 1 area ratio and 16 : 1 area ratio, respectively and the cathode contact area is 1.75×10^{-4} cm^2. They are measured at 1 MHz with HP4275A multifrequency LCR meter. The epitaxial layer is composed of a 2000 Å, 5×10^{18} cm^{-3} Si-doped n^+ layer, a 2000 Å, 3×10^{17} cm^{-3} Si-doped n layer, a 5000 Å, 5×10^{15} cm^{-3} Be-doped p^- layer and a 5000 Å, 10^{19} cm^{-3} Be-doped p^+ layer. The capacitance transition occurs in the bias range of 6–8 V. When the reverse bias voltage is small, the capacitance characteristics are flat because of the thick p^- layer. It is found that the capacitance ratios are well matched to the area ratios of layout patterns.

III. Microwave Characteristics

Microwave C-V characteristics show large differences compared with the quasistatic C–V characteristics in Fig. 3. The devices are fabricated on an epi layer grown on GaAs (100) substrate by Molecular Beam Epitaxy (MBE) and the epi layer consists of a 1000 Å n^+ layer with 5×10^{18} cm^{-3}, a 4000 Å n layer with 10^{17} cm^{-3} and a 5000 Å p^+ layer with 3×10^{19} cm^{-3}. On-wafer measurement is performed to characterize the varactor diode with a Wiltron 360 vector network analyzer and Cascade on-wafer probes. The measured device has about 10 : 1 area ratio and 3 μm spacings between the floating contacts and the cathode, which is also 3 μm wide (W_1 in Fig. 1) and ~22 μm long.

The capacitance as a function of the bias voltage in the frequency range of 1–7 GHz is shown in Fig. 4. As the frequency increases, the rate of capacitance change decreases. The capacitance ratio of C (0 V)/C (−4 V) is about 5.4 and that of C (1 V)/C (−4 V) is about 18.5 at 1 GHz. These capacitance ratios are not well matched to those of the layout patterns. This is because of side access resistance between the cathode and the floating contacts, which becomes relatively large compared with the reactance under the floating contacts in the high frequency operation. The resistance distorts the conventional C–V characteristics of the diode and produces its peculiar characteristics.

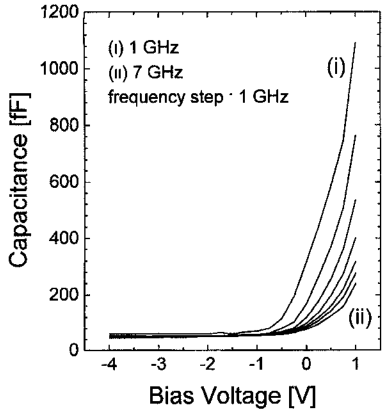

Fig. 4. The capacitance as a function of the bias voltage extracted from microwave measurements in the frequency range of 1–7 GHz. The area ratio of the cathode region and the floating contact regions is about 10 and the spacing between the cathode and the floating contacts is 3 μm. The cathode is 3 μm wide and $\sim 22\,\mu$m long.

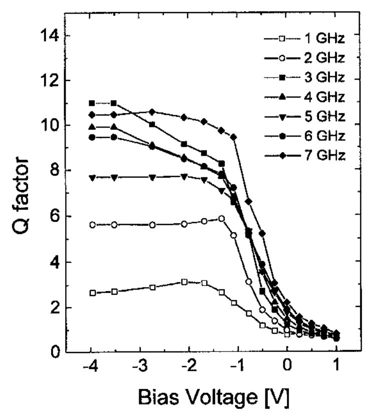

Fig. 5. The quality factor versus the bias voltage extracted from microwave measurements in the frequency range of 1–7 GHz. The geometrical parameters of the measured device are same as those in Fig. 4.

Fig. 5 shows the quality factor versus the bias voltage in the frequency range of 1–7 GHz. As the reverse bias voltage increases, the value of the quality factor Q increases. Also, the Q value increases with the frequency in the bias range of capacitance transition. This is due to the combined effects of the large capacitance at low frequency and the large side access resistance. In general, the quality factor of the area-variable varactor diode is not a monotonic function of the frequency and has the minimum and the maximum at specified frequencies depending on the geometrical structure.

Ignoring parasitic capacitances and lead inductances, the area-variable varactor diode can be simply modeled as the series resistance, R_s, the capacitance under the cathode, C_c, the side access resistance, R_x, and the capacitance under the floating contacts, C_s. So, the equivalent series capacitance, C_{eq}, and the quality factor, Q, can be expressed as

$$C_{eq} = \frac{\omega^2 R_x^2 C_s^2 C_c^2 + (C_s + C_c)^2}{\omega^2 R_x^2 C_c C_s^2 + C_c + C_s} \tag{1}$$

$$Q = \frac{\omega^2 R_x^2 C_s^2 C_c + C_s + C_c}{\omega[\omega^2 R_s R_x^2 C_s^2 C_c^2 + R_x C_s^2 + R_s(C_c + C_s)^2]}. \tag{2}$$

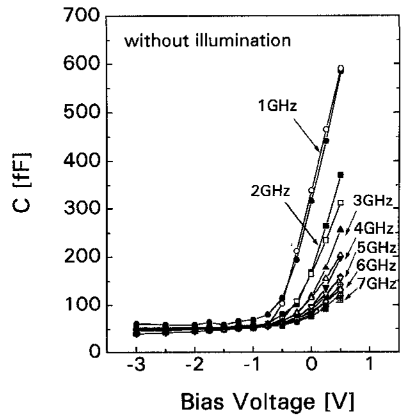

Fig. 6. The capacitance versus the bias voltage from the measured results and the equivalent circuit model in the frequency range of 1–7 GHz without optical illumination (dark condition). The modeled data are calculated from the equivalent circuit with $C_c = 70$ fF, 10 : 1 area ratio and $R_x = 955\,\Omega$. (The dark solid symbols and "+" marked open symbols indicate the measured data. The open symbols and the dotted lines indicate the modeled data.)

At a specific frequency, the capacitance ratio is saturated due to nonzero access resistance in spite of the increase of the area ratio as predicted by (1).

The capacitance value with the bias voltage extracted from the equivalent circuit model is compared with the measurement data in Fig. 6. The modeled C_c of 70 fF is calculated from the cathode area and the area ratio is 10. The slight difference between the modeled capacitance and the measured capacitance is caused by parasitic elements not considered in the equivalent circuit. Reduction of the side access resistance, R_x, leads to a sharp and large capacitance change. To improve the quality factor, the spacing between the cathode and the floating contact must be very small and/or active channel transport characteristics must be superior along the direction of the cathode to the floating contact.

IV. Photoresponse Results

The properties of the diode are quite sensitive to the access resistance, which can be significantly modified by optical illuminations on the access area. In order to examine the possible optical controllability of the diode, the microwave characteristics are investigated under optical illumination. The used laser diode has a 670 nm wavelength and its power can be adjusted with an external current control.

Fig. 7 shows the capacitance variation with the bias voltage at 1 GHz under various illumination intensities. The capacitance value under illumination is normalized to that of dark condition at each bias voltage, which is set to 100% at each bias voltage. The input light powers estimated from illuminated area are 220, 737, and 1045 nW. The capacitance at -0.75 V with 1045 nW input light power is $\sim$4.5 times as large as that of dark condition. As the input light power increases, the capacitance increases nonlinearly with the input light powers. This is because the access resistance is decreased due to the generation of electron-hole pairs by the light absorbed in the access area [17]. The capacitance variations at forward biases are small because the access resistance is already small at forward biases.

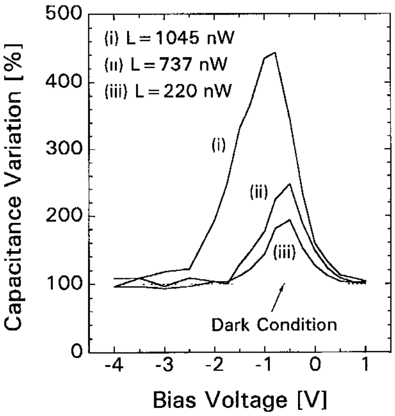

Fig. 7. The capacitance variation with the bias voltage under optical illumination. The input light powers are 220, 737, and 1045 nW. The capacitance value is extracted at 1 GHz and the capacitance value under dark condition is normalized to 100% at each bias voltage.

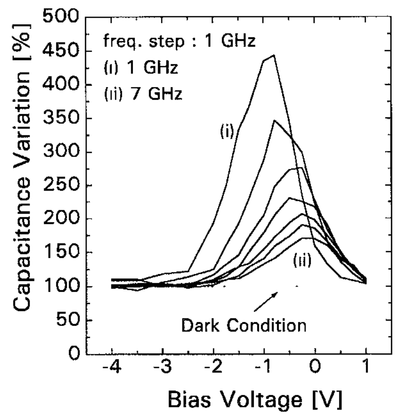

Fig. 9. The capacitance variation with the bias voltage in the frequency range of 1–7 GHz under optical illumination (input light power, L = 1045 nW). The capacitance value under dark condition is normalized to 100% at each bias voltage and each frequency.

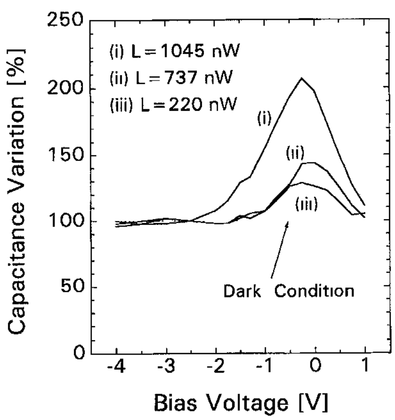

Fig. 8. The capacitance variation with the bias voltage under optical illumination. The input light powers are 220, 737, and 1045 nW. The capacitance value is extracted at 5 GHz and the capacitance value under dark condition is normalized to 100% at each bias voltage.

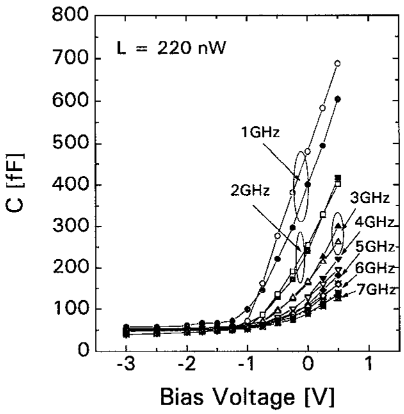

Fig. 10. The capacitance versus the bias voltage from the measured results and the equivalent circuit model in the frequency range of 1–7 GHz under illumination (input light power, L = 220 nW). The modeled data are calculated from the equivalent circuit with C_c = 70 fF, 10 : 1 area ratio and $R_x = 630\,\Omega$. (The dark solid symbols and "x" marked open symbols indicate the measured data. The open symbols and the dotted lines indicate the modeled data.)

The capacitance variations with the bias voltages at 5 GHz under illuminations are also shown in Fig. 8 and the maxima of the capacitance variations move toward forward bias region, compared with the data at 1 GHz. The magnitude of the variation is reduced to almost half of that in Fig. 7.

Fig. 9 shows the capacitance variations with the bias voltages in the frequency range of 1–7 GHz under 1045 nW light power illumination. As the frequency increases, the capacitance variation decreases and the maxima of the variation curves move toward forward bias. The maximum capacitance variation changes from ~170% at 7 GHz to ~450% at 1 GHz. This can be simply explained by (1). The frequency increase results in the decrease of the equivalent series capacitance, C_{eq}.

All these capacitance variations due to optical illuminations can be simply modeled with the variation of the access resistance. Fig. 10 shows the measured capacitances and the simulated data by the simple equivalent circuit model in the frequency range of 1–7 GHz under optical illumination (input light power, L = 220 nW). The dark solid symbols and "x" marked open symbols indicate the measured data. The open symbols and the dotted lines indicate the modeled data. Little discrepancy between the measured data and the modeled data at 1 GHz is expected to be due to complex optical responses of the depletion regions and the simple circuit model that precludes parasitic capacitances and lead inductances. All these capacitance variations of the varactor diode are large enough to be utilized in optically controllable circuits such as oscillators and mixers.

V. Conclusion

In order to obtain various C–V characteristics in a single chip, we had proposed a novel area-variable varactor diode. Its microwave characteristics and capacitance variations due to optical illuminations were investigated in the frequency range of 1–7 GHz. It was demonstrated that the capacitance ratio at 1 GHz was maximally 18.5 and strongly depended on the access resistance between the cathode and the floating contacts. Using a simple equivalent circuit model we explained the capacitance value in the frequency range of 1–7 GHz. It was also shown that the C–V characteristics were quite different at each frequency and the capacitance ratio decreased as the frequency increased. The varactor diode showed large capacitance variations under optical illuminations. As the input light power increased, the capacitance variation increased and its maximum change of 450% was demonstrated. The capacitance variation was modeled by modifying the access resistance. Finally, it was mentioned that further optimization of the area-variable varactor diode would make it possible to use it in optically controlled microwave circuits.

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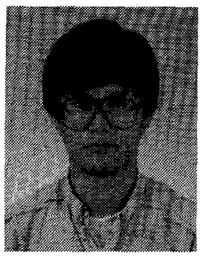
REFERENCES

[1] U. Karacaoglu and I. D. Robertson, "High selectivity varactor-tuned MMIC bandpass filter using lossless active resonators," in *IEEE Microwave Millimeter-Wave Monolithic Circuits Symp.*, 1994, pp. 237–240.
[2] S. R. Chandler, I. C. Hunter, and J. G. Gardiner, "Active varactor tunable bandpass filter," *IEEE Microwave Guided Wave Lett.*, vol. 3, no. 3, pp. 70–71, Mar. 1993.
[3] D. M. Krafcsik, S. A. Imhoff, D. E. Dawson, and A. L. Conti, "A dual-varactor analog phase shifter operating at 6–18 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 12, pp. 1938–1941, Dec. 1988.
[4] B. N. Scott and G. E. Brehm, "Monolithic voltage controlled oscillator for X- and Ku-bands," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, no. 12, pp. 2172–2177, Dec. 1982.
[5] E. Reese., Jr. and J. M. Beall, "Optimized X and Ku band GaAs MMIC varactor tuned FET oscillators," in *IEEE MTT Sym.*, 1988, pp. 487–490.
[6] J. N. Poelken and R. S. Robertson, "A comparison of planar doped barrier diode performance versus Schottky diode performance in a single balanced, MIC mixer with low LO drive," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 6, pp. 1241–1246, June 1995.
[7] M. J. W. Rodwell, M. Kamegawa, R. Yu, M. Case, E. Carman, and K. S. Giboney, "GaAs nonlinear transmission lines for picosecond pulse generation and millimeter-wave sampling," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-39, no. 7, pp. 1194–1204, July 1991.
[8] D. W. van der Weide, "Delta-doped Schottky diode nonlinear transmission lines for 480 fs, 3.5 V transients," *Appl. Phys. Lett.*, vol. 65, no. 7, pp. 881–883, Aug. 1994.
[9] M. A. Frerking and J. R. East, "Novel heterojunction varactors," *Proc. IEEE*, vol. 80, no. 11, pp. 1853–1860, Nov. 1992.
[10] W. C. B. Peatman, T. W. Crowe, and M. Shur, "A novel Schottky/2-DEG diode for millimeter- and submillimeter-wave multiplier applications," *IEEE Electron. Dev. Lett.*, vol. 13, no. 1, pp. 11–13, Jan. 1992.
[11] R. J. Hwu, "A mm-wave high power monolithic back-to-back varactor diode frequency tripler," *Microwave J.*, pp. 240–253, May 1993.
[12] A. Rydberg, H. Grönqvist, and E. L. Kollberg, "Millimeter- and submillimeter-wave multiplier using quantum-barrier-varactor (QBV) diodes," *IEEE Electron. Dev. Lett.*, vol. 11, no. 9, pp. 373–375, Sept. 1990.
[13] S. M. Nilson, H. Grönqvist, H. Hjelmgren, A. Rydberg, and E. L. Kolberg, "Single barrier varactors for submillimeter wave power generation," *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 4, pp. 572–580, Apr. 1993.
[14] A. V. Räisämen, "Frequency multipliers for millimeter and submillimeter wavelengths," *Proc. IEEE*, vol. 80, no. 11, pp. 1842–1852, Nov. 1992.
[15] D. W. Kim, J. H. Son, S. C. Hong, and Y. S. Kwon, "A novel area-variable varactor diode," in *21st Int. Symp. on Comp. Semiconductor*, Sept. 1994, pp. 733–736.
[16] P. Callaghan, S. K. Suresh Babu, N. J. Gomes, and A. K. Jastrzebski, "Optically frequency modulated 6 GHz MMIC oscillator," in *25th European Microwave Conf.*, 1995, pp. 155–159.
[17] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981.



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