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Frequency dependence of junction capacitance of BPW34 and BPW41 p–i–n photodiodes

HABIBE BAYHAN and ŞADAN ÖZDEN
Physics Department, Faculty of Art and Science, University of Muğla, 48000 Muğla, Turkey
E-mail: hbayhan@mu.edu.tr

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Abstract. This article investigates the frequency dependence of small-signal capacitance of silicon BPW34 and BPW41 (Vishay) p–i–n photodiodes. We show that the capacitance-frequency characteristics of these photodiodes are well-described by the Schibli and Milnes model. The activation energy and the concentration of the dominant trap levels detected in BPW34 and BPW41 are 280–330 meV and 1.1×10^{12}–1.2×10^{12} cm^{-3}, respectively. According to the high-frequency C–V measurements, the impurity concentrations are determined to be about 5.3×10^{12} and 1.9×10^{13} cm^{-3} in BPW41 and BPW34, respectively using the method of $\Delta V/\Delta(C^{-2})$ vs. C.

Keywords. BPW34; BPW41; p–i–n; capacitance; frequency dependence.

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1. Introduction

Among a number of high-speed and high-sensitive silicon-based p–i–n photodiodes, BPW34 and BPW41 are the two photodiodes that have been used in various applications in visible (400–1000 nm) and near infrared (>900 nm) region of the spectrum, respectively [1]. The space-charge region in these photodiodes is a key issue for the device performance. The i-layer must have sufficient carrier transport properties and field profile for efficient photodiode operation. Since field profile and carrier life-times are strongly related to the mid-gap density of states, understanding and control of these localized defect states still are important to improve the properties of these devices further. The characteristics of deep trapping states in the space-charge region of a p–n or Schottky junction can be obtained by several techniques such as capacitance vs. voltage and frequency [2,3] and deep-level transient spectroscopy.

In this paper the frequency and the temperature dependence of small-signal capacitance of silicon-based BPW34 and BPW41 (Vishay) detectors have been studied. The model of Schibli and Milnes [2], which is based on the presence of a single

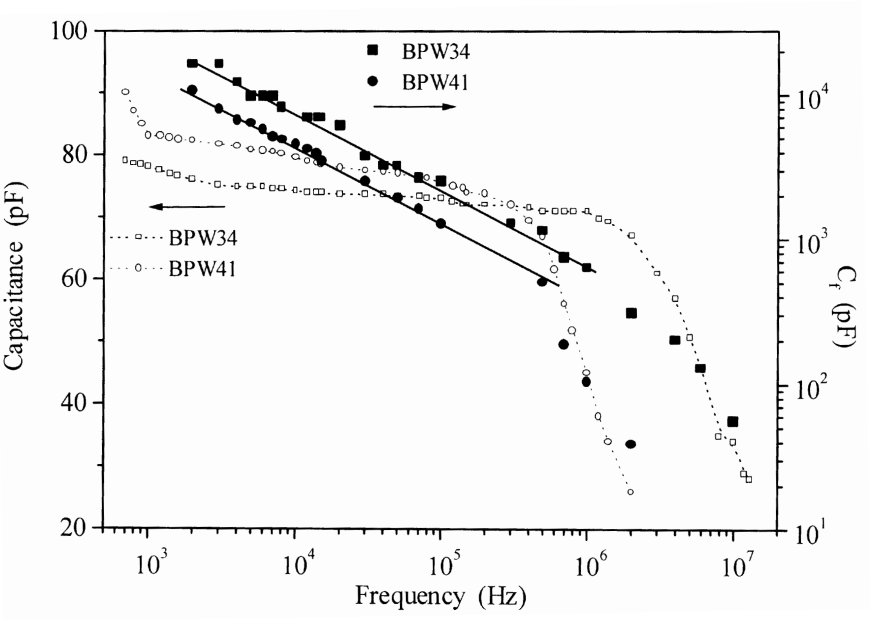

Figure 1. The C and C_f vs. f characteristics of p–i–n photodiodes at 300 K. The solid lines correspond to best linear fits.

dominant deep trap level in n^+p junctions, was used to estimate the activation energy and the trap density of the dominant defect level in the bandgap of the photodiodes. The impurity concentrations of these photodiodes were evaluated using high-frequency capacitance–voltage characteristics and the model of Zohta [4].

2. Experimental

Capacitance–frequency measurements were carried out using Hewlett Packard HP 4192A impedance analyser operating at frequencies 100 Hz to 10 MHz. The device was mounted in the sampler holder of the helium cryostat (Oxford) and the measurements were made in vacuum at temperatures between 100 K and 300 K. Temperature-dependent junction capacitance measurements were performed at zero bias and the amplitude of the AC signal was at 10 mV. The junction areas are given as 7.5 mm^2 and 7.25 mm^2 for BPW41 and BPW34, respectively.

3. Results and discussions

The typical room-temperature capacitance–frequency (C–f) characteristics of BPW34 and BPW41 are given in figure 1. The capacitance of both photodetectors shows no frequency dependence in a very broad frequency range from well below 100 kHz to about 10^5 Hz. There occurs a monotonous decrease in the capacitance data

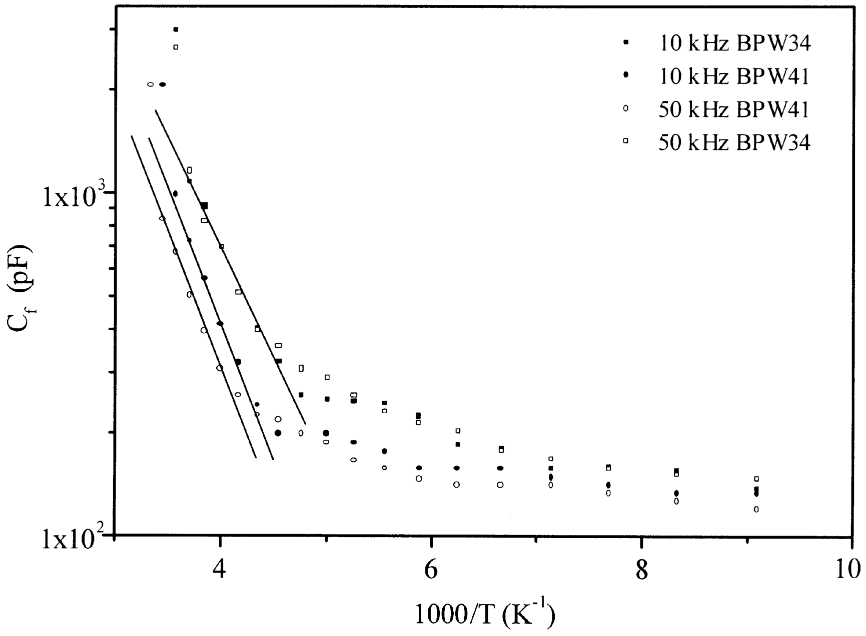

Figure 2. The C_f vs. T^{-1} characteristics of p–i–n photodiodes. The solid lines correspond to best linear fits.

at frequencies above 10^6 Hz and 3×10^5 Hz for BPW34 and BPW41, respectively. This noticeable variation indicates that the concentration of deep impurities in the photodetectors may be very high. When the deep impurity concentration is higher than that of shallow trap states, the Schibli–Milnes model [2] can be used to define the frequency dependence of the junction capacitance. According to this model, the junction capacitance can be represented by a series combination of frequency-independent (bias-dependent) capacitance C_DC and a frequency-dependent capacitance C_f as $C^{-1} = C_\mathrm{DC}^{-1} + C_\mathrm{f}^{-1}$ where

$$C_\mathrm{f} = A\left(\frac{2\varepsilon q^2}{kT}N_\mathrm{T}\frac{\omega_1}{\omega}\right)^{1/2}, \tag{3.1}$$

$$\omega_1 = c_\mathrm{p}\frac{N_v}{g}\exp\left(-\frac{qE_\mathrm{T}}{kT}\right), \tag{3.2}$$

where $\omega = 2\pi f$ is the measurement frequency, c_p is the hole capture probability when the center is ionised, g is the degeneracy factor of the deep level, A is the junction area, N_T is the trap density and E_T is the activation energy of the deep trap. The other symbols have their usual meanings. If the capture cross-section is relatively temperature-independent, the C_f vs. $1000/T$ variation could yield half of the activation energy of the deep impurity.

From figure 1, C_DC values are estimated to be about 72 and 80 pF for BPW34 and BPW41, respectively. These values were used to calculate C_f from the measured C–f and C–T (not shown here) variations. Figure 1 also reveals that C_{f} depend on the frequency as $C_{\mathrm{f}} \propto f^{-0.51}$ and $C_{\mathrm{f}} \propto f^{-0.53}$ for BPW34 and BPW41, respectively. These are very close to the theoretical variation of $f^{-0.5}$ given by eq. (3.1). Arrhenius plots of the frequency-dependent capacitance C_{f} of both photodiodes at 10 and 50 kHz are given in figure 2. For temperatures approximately lower than 220 K, C_{f} values decreased only slightly whereas at higher temperatures C_{f} showed a strong temperature dependence which led to the calculation of the trap depths of about 280 ± 2 meV and 330 ± 2 meV from eqs (3.1) and (3.2) for BPW34 and BPW41, respectively.

Based on the model [2], the break-point frequency, ω_{B} is the frequency where $C_{\mathrm{f}} = C_{\mathrm{DC}}$ and is given as $\omega_{\mathrm{B}} = (4qV_{\mathrm{j}}/kT)\omega_1$, where V_j is the total junction voltage. At room temperature, the total DC voltages measured across BPW34 and BPW41 are about 0.55 V and 0.32 V, respectively. The break-point frequencies are determined from figure 1 as $\omega_{\mathrm{B}} \cong 2\pi(1.9 \times 10^6)$ for BPW34 and $\omega_{\mathrm{B}} \cong 2\pi(4.1 \times 10^5)$ for BPW41. The value of ω_1 for both devices is calculated and then the densities of the traps are estimated to be about 1.1×10^{12} cm^{-3} for BPW34 and 1.2×10^{12} cm^{-3} for BPW41 from the slope of C_{f}^2 vs. ω^{-1} plots and with the help of eq. (3.1). The N_{T} values were also calculated by using depletion region widths, w, of about 10.5 and 9.80 μm obtained from the C_{DC} values and $w^2 = 2\varepsilon V_{\mathrm{j}}/qN_{\mathrm{T}}$ as about 6.5×10^{12} cm^{-3} and 4.3×10^{12} cm^{-3} BPW34 and BPW41, respectively.

Although we do not know the definite energy band structure and the doping profiles of different layers in these photodetectors, it is generally accepted that the i-region is slightly n-type. Thus a p–n junction is preferentially formed at the p–i interface. We can reasonably infer that the capacitance–frequency characteristics are mainly determined by the defect states possibly located at or close to the p–i interface. If we assume that the n–i junction is nearly ohmic, than the typical p–i–n photodiode can be modelled as a Schottky-type junction in the presence of defect states near or at the p–i interface [5]. Since the calculation of Schottky junction is the same as that of n$^+$p junction in the Schibli–Milnes model, we think that these p–i–n photodiodes can possibly be modelled as a Schottky type having a single space-charge region.

The frequency dependence of C and $\Delta V/\Delta(C^{-2})$ are investigated according to the model proposed by Zohta [6–8]. In this model the DC voltage difference ΔV between two biases is given as

$$\Delta V = (q\varepsilon A^2/2)[(N_{\mathrm{D}} - N_{\mathrm{A}} + N_{\mathrm{T}}) - (N_{\mathrm{T}}\lambda_0/\varepsilon A)C]\Delta(C^{-2}), \tag{3.3}$$

where N_{D} is the donor concentration and N_{A} is the acceptor concentration and λ_0 is the position at which the Fermi level crosses the deep level. If a test signal frequency of the capacitance measurement is so high, it is assumed that λ_0 is independent of bias voltage. Thus, $N_{\mathrm{D}} - N_{\mathrm{A}} + N_{\mathrm{T}}$ can be estimated from the intercept of linear fit at $C = 0$ using a plot of $\Delta V/\Delta(C^{-2})$ vs. C.

The capacitance–voltage data of the p–i–n devices are found to be almost independent of the applied frequency in the range of 100 to 1000 kHz at room temperature. The C–V values measured at 1 MHz frequency (not shown here) are used to obtain $\Delta V/\Delta(C^{-2})$ vs. C characteristics as given in figure 3. The $N_{\mathrm{D}} - N_{\mathrm{A}} + N_{\mathrm{T}}$ values are determined to be about -1.9×10^{13} cm^{-3} and -5.3×10^{13} cm^{-3} for BPW34 and BPW41, respectively. Substituting the values of N_{T} calculated from

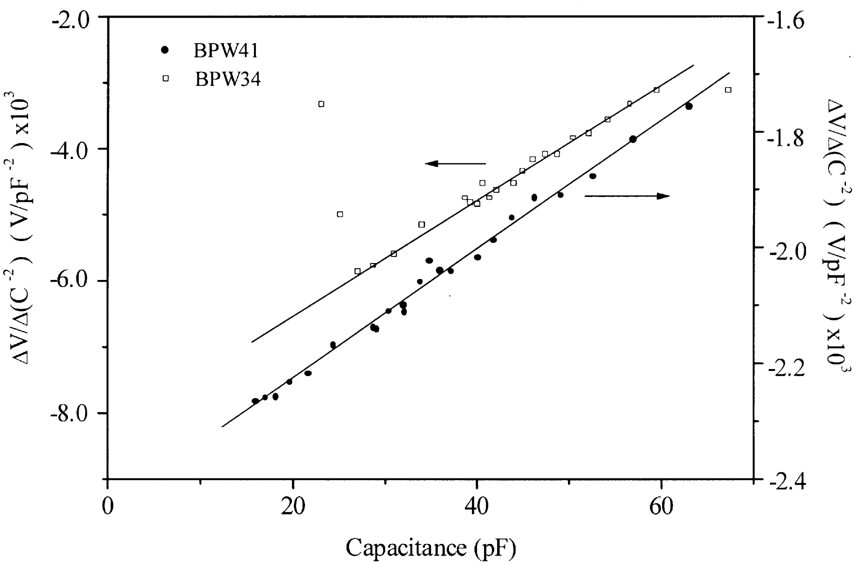

Figure 3. $\Delta V/\Delta(C^{-2})$ vs. C plots of p–i–n photodiodes at various frequencies. The solid lines correspond to best linear fits.

the slope of C_f^2 vs. ω^{-1} plots into $N_D - N_A + N_T$, we can estimate $N_D - N_A$ as about -2.0×10^{13} cm^{-3} and -5.4×10^{13} cm^{-3} for BPW34 and BPW41, respectively. The sign $-$ represents the charge state of $N_D - N_A + N_T$ in the space-charge region. So, it was suggested that the capacitance–frequency and capacitance–temperature characteristics of the typical photodiode might possibly be determined by deep impurities in the p layer. It is then reasonable to consider that there are no deep impurities in both n and i layers and the response of free carriers is fast enough. Thus, these layers can be regarded as metal-like layers during the measurement of the capacitance and the p–i–n junction can possibly be modelled just like a Schottky junction.

4. Conclusion

The frequency dependence of small-signal capacitance of p–i–n BPW34 and BPW41 (Vishay) detectors have been studied. We show that the model of Schibli and Milnes can still be used to describe the capacitance change with frequency and temperature of both photodiodes, by considering a single dominant level. The impurity concentrations were estimated using high frequency (1 MHz) C vs. V data and plots of $\Delta V/\Delta(C^{-2})$ vs. C according to the model proposed by Zohta. The good agreement between the experimental data and the models proposed by Schibli–Milnes and Zohta suggest that the observed single trap levels in both photodiodes are associated with the p-type layer rather than with the i-layer.

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