Investigation of the spatial resolution of the light-addressable potentiometric sensor

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Received 14 September 1999; received in revised form 3 March 2000; accepted 4 March 2000

Abstract

The spatial resolution of the light-addressable potentiometric sensor (LAPS) is investigated both theoretically and experimentally. For a theoretical analysis, the diffusion equation for minority charge carriers in the semiconductor was solved. The results suggest that by thinning the semiconductor wafer, the spatial resolution of the LAPS is no longer limited by the bulk minority charge carrier diffusion length. Spatial resolution in the micrometer range should thus be possible. For an experimental analysis, the effective diffusion length of light-generated charge carriers parallel to the sensor surface was measured. The results show that by increasing the doping density and by thinning the semiconductor substrate, spatial resolution of about 15 μm is obtained. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Light-addressable potentiometric sensor; LAPS; Spatial resolution; Surface potential sensor

1. Introduction

The light-addressable potentiometric sensor (LAPS) is a surface potential sensor with the option of spatial resolution [1–3]. It comprises an electrolyte–insulator–semiconductor (EIS) or a metal–insulator–semiconductor (MIS) structure, which is biased with a DC voltage, and a modulated light source (see Fig. 1). By illuminating parts of the semiconductor substrate, a localized photocurrent is generated, of which the amplitude depends on the surface potential at the illuminated region. By measuring the amplitude of the photocurrent while the light pointer is scanned across the surface of the semiconductor, a map of the surface potential distribution is obtained [4–10]. For such kind of imaging, high spatial resolution is crucial.

Previous theoretical calculations predict that for thick semiconductor substrates, spatial resolution is limited by the bulk diffusion length of the minority charge carriers [11]. Experimental studies, which have been reported recently, suggest that for thin semiconductor substrates, spatial resolution is no longer limited by the diffusion length of minority charge carriers, and thus is better than for thick semiconductor substrates [7]. To quantitatively understand these experimental findings, in this work the existing theory was extended to describe spatial resolution for thin semiconductor substrates.

Different strategies are conceivable to experimentally investigate the spatial resolution of the LAPS. Most often, the LAPS surface is modified, so that artificial surface potential patterns are generated. In this way, spatial resolution is defined as the size of the smallest structure, which can be resolved by mapping the potential distribution of this pattern with the LAPS. One possible modification is to coat parts of the semiconductor surface with dielectric materials (e.g. photoresist, or LaF3), which leads to different surface potentials at untreated and masked areas [7,12,13]. Alternatively, a surface potential pattern can be created by irradiating parts of the LAPS surface with UV light prior to experiments [11]. In order to quantify spatial resolution with this method, many patterns with various sizes have to be probed. Therefore, in this
In this study, an alternative experimental method to investigate the spatial resolution of the LAPS is described. The idea is to measure diffusive propagation of light-generated charge carriers at an edge on the LAPS surface, where only at one side a photocurrent can flow. This can be realized by coating only parts of the LAPS surface with a thin metal layer, to which the bias voltage is applied (see Fig. 2). Upon illuminating metal-free parts of the surface no photocurrent will flow, because of the open electric circuit: Without bias, at best, a small space charge region due to surface states can exist. If light-generated holes and electrons are separated in the floating field of this space charge region, a counteracting field is created, which revokes charge separation. In contrast, there will be a photocurrent if metallized areas are illuminated: In this case, a space charge region is created by the applied bias voltage. If charge carriers are separated in the static electric field of this space charge region, because of the applied bias voltage, no counteracting field is created, but, rather, charge separation is completed by charge transport in the voltage source. Now, the spatial resolution of the LAPS can be determined in the following way. The light pointer is scanned from a metal covered to a naked region. If the non-metallized surface is illuminated near to metallized parts, light-generated charge carriers can diffuse to metallized regions and thus close the electric circuit and create a photocurrent. Therefore, spatial resolution can be determined by measuring the decay of the amplitude of the photocurrent vs. the lateral distance of the light pointer to the metallized region. The decay length of this curve can be interpreted as the effective lateral diffusion length of light-generated charge carriers, which in this study is regarded as a measure for spatial resolution.

2. Theory

For a general, detailed analysis of the photocurrent, the transport equations for electrons and holes in the semiconductor have to be solved. In Eqs. (1) and (2), the transport equations for holes are given. Analogues equations can be derived for electrons.

\[
\frac{\partial}{\partial t} p = G - \frac{1}{\tau} \rho + D \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \rho + \mu \times \left( \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \right) (pE) \]  
(1)

\[ j_z = \mu \left( pE_z - \frac{kT}{e} \frac{\partial}{\partial z} \rho \right) \]  
(2)

Here, \( p \) [m\(^{-3}\)] denotes the density of free holes, \( G \) [m\(^{-3}\) s\(^{-1}\)] the generation rate of electron–hole pairs due to illumination, \( \tau \) [s], \( D \) [m\(^2\) s\(^{-1}\)] and \( \mu \) [m\(^2\) V\(^{-1}\) s\(^{-1}\)] the lifetime, the diffusion coefficient, and the mobility of free holes in the bulk of the semiconductor, respectively. \( E \) [V m\(^{-1}\)] = \( E_z \) describes the electric field in the semiconductor due to the applied bias voltage and \( j_z \) [m\(^{-2}\) s\(^{-1}\)] the resulting current density of holes perpendicular to the surface. \( k, T, e \) are the Boltzmann constant, the absolute temperature, and the electron charge, respectively. The first part of Eq. (1) describes the light-driven generation and the second part the recombination of free holes. The third part describes isotropic diffusion and the last part the
drift of holes in the electric field of the semiconductor. Due to its complex structure, Eq. (1) cannot be solved analytically in general, although solutions for special conditions have been reported [15]. However, in this study, Eq. (1) was solved analytically neglecting the drift term. This is equivalent to splitting Eq. (1) into two parts, which describe movement of charge carriers in the bulk and at the surface, respectively. In the bulk of the semiconductor, no electric field exists due to electrostatic screening. Thus, movement of charge carriers can be simply described by isotropic diffusion and is equivalent for electrons and holes. Lateral diffusion of charge carriers parallel to the LAPS surface then accounts for limited spatial resolution [7,11]. If free charge carriers eventually reach the space charge region located at the surface of the semiconductor, holes and electrons are separated in its electric field. This process accounts for the generation of the photocurrent and is described by the drift term.

In order to track the diffusion-driven lateral spread of photo-generated charge carriers in the bulk of the semiconductor after an initial flash of light, by neglecting the drift term, the transport Eq. (1) can be simplified to a diffusion equation, including bulk recombination [3,11]. Since only minority charge carriers contribute to the photocurrent, in Eq. (1) can now be solved analytically using Eqs. (6) and (8), analogously to the calculation reported for thick semiconductor substrates.

Following an approach that has been described in a previous study [11], the spatial resolution is calculated for illumination of the semiconductor wafer both from its frontside and its backside. \( L \) is the penetration depth of photons in the semiconductor and the bulk diffusion length \( L \) of holes is defined as \( L^2 = D \tau \). In the case of thin wafers, i.e. \( d \ll L \), Eq. (8) is a solution of Eqs. (3)–(5) [16,17].

\[
\Delta p = \exp \left( -\frac{t}{\tau} \right) \frac{1}{4\pi D t} \sum_{n=1}^{\infty} \sin \left( \frac{n\pi z}{d} \right) \\
\times \exp \left( -\frac{n^2\pi^2 t}{d^2} \right) \cdot \int_{z=0}^{\infty} \int_{y=0}^{\infty} \int_{x=-\infty}^{\infty} \Delta p_0 \exp \left( \frac{(x-x')^2 + (y-y')^2}{4Dt} \right) \sin \left( \frac{n\pi z}{d} \right) dx'dy'dz' \tag{8}
\]

Here \( \Delta p_0 = \Delta p(t = 0) \) denotes the distribution of light-generated holes after an initial light flash. For thick wafers, i.e. \( d \gg L \), the solution of Eqs. (3)–(5) has already been described in Eqs. (3) and (8) in Ref. [11]. Eq. (7) can now be solved analytically using Eqs. (6) and (8), analogously to the calculation reported for thick semiconductor substrates.

3. Materials and methods

As semiconductor substrates, different n-doped silicon chips (CrysTec, Berlin, Germany) with an area of 20 × 20 mm, a specific resistance \( \rho \) of 5–1350 \( \Omega \) cm and a thickness \( d_s \) of 0.38–1 mm were used (see Table 1). Additionally, one semiconductor substrate was used, which was composed of a thin epi-film (\( d_s = 3 \mu m \)) with low doping density (\( \rho = 10 \Omega \) cm), grown on a 380-\( \mu m \)-thick highly doped silicon chip. At the backside of the chips, an ohmic contact was created. The frontside was coated either with a thick (10 nm SiO\(_2\) + 30 nm Si\(_3\)N\(_4\)) or a thin (30 nm SiO\(_2\) + 60 nm Si\(_3\)N\(_4\)) insulating layer. A 25-nm-thick NiCr layer was evaporated on half of the LAPS surface, whereas the other half remained uncoated.

Table 1

<table>
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<tr>
<th>No.</th>
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<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>5–10</td>
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</tr>
<tr>
<td>3</td>
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<td>0.003/0.38</td>
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<tr>
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<tr>
<td>5</td>
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</table>

Composition of the probed LAPS chips. \( \rho \) denotes the specific resistance and \( d_s \) the total thickness of the n-doped Silicon substrate. The semiconductor substrate no. 3 consists of a thin epi-film (\( d_s = 3 \mu m \)) with low doping density (\( \rho = 10 \Omega \) cm), grown on a 380-\( \mu m \)-thick highly doped (\( \rho = 0.005–0.02 \Omega \) cm) silicon wafer.
(see Fig. 2). A bias voltage \( U \) was applied between this metal layer and the ohmic contact at the backside of the silicon wafer. As light pointer, a 10-mW semiconductor laser diode with 690 nm wavelength (Toshiba, Schäfer and Kirchhoff, Hamburg, Germany), which was modulated at 10 kHz, was used. To obtain small spot diameters, the light spot on the silicon was focused and simultaneously viewed, by using a beam splitter and the 20 \( \times \) objective of an optical microscope (Axiotech, Zeiss, Oberkochen, Germany). The amplitude \( I \) of the resulting photocurrent was preamplified with a current-to-voltage converter and recorded using a phase sensitive lock-in amplifier. The whole set-up was shielded with a copper box, to exclude ambient light and to minimize background noise. For experiments, the light pointer was scanned across the surface of the device in \( x \)-direction. Scans started in the metal covered region \( x < 0 \), crossed the borderline \( x = 0 \) and ended in the uncovered, naked region \( x > 0 \). During scans, photocurrent–bias voltage \( I(U) \) curves were recorded.

A similar experiment was carried out to determine the radius of the light pointer \( r_L \). Here, one side of the LAPSL surface was covered with a thick (80 nm) and the other side with a thin (25 nm) NiCr layer. Again, a bias voltage was applied between the metal covered front surface and the ohmic contact at the backside. While recording \( I(U) \) curves, the modulated light pointer was scanned from the thick- \( (x < 0) \) to the thin-coated \( (x > 0) \) part of the surface.

### 4. Results

The results, which have been obtained by the theoretical analysis of the spatial resolution, are summarized in Tables 2 and 3. It turns out that diffusion of holes in the bulk of the semiconductor can be mainly described by the ratio of three length scales: (i) the bulk diffusion length of free holes \( L_U \); (ii) the extension of the bulk of the semiconductor \( d \); and (iii) the penetration depth \( L_r \) of the photons in the semiconductor substrate. In Table 2, the predicted spatial resolution \( r_{\text{bc}}^2 \) for thick \( (d \gg L) \) and thin \( (d \ll L) \) semiconductor substrates in the case of frontside illumination is shown. The results suggest that for thick semiconductor substrates \( (d \gg L) \), spatial resolution is limited by the bulk diffusion length of free holes. Only if, due to a small penetration depth of photons \( (L_r \ll L) \), holes are generated near the space charge region, spatial resolution is improved [11]. For thin semiconductors, spatial resolution no longer depends on the diffusion length, but is determined by the thickness of the semiconductor substrate. For backside illumination, only the case of thin semiconductor substrates could be considered (see Table 3), since for infinitely thick semiconductor substrates \( (d \to \infty) \), the charge carriers recombine before they reach the space charge region and no photocurrent flows. For thin semiconductor substrates, spatial resolution is basically limited by the thickness of the semiconductor substrate. However, regardless if the semiconductor substrate is illuminated from the front or the back, the theoretical analysis suggests that spatial resolution is improved by using thin semiconductor substrates. These analytical results are in good agreement with numerical estimations, which have been reported by Nakao et al. [7].

In the following, the results of the experimental findings are described. A typical photocurrent–voltage–distance \( I(U, x) \) curve, which was obtained according to the protocol sketched in Fig. 2, is plotted in Fig. 3. Photocurrent–voltage \( I(U, x = \text{const}) \) curves, which are cross-sections of the \( I(U, x) \) curves at constant distances \( x \), showed typical sigmoidal shapes (see Fig. 5a). Basically, no photocurrent flowed in the case of accumulation \( (U > 0) \), and the maximum photocurrent, if the MIS structure was biased into inversion \( (U < 0) \). A photocurrent–distance \( I(U = \text{const}, x) \) curve, which is the cross-section at \( U = -8 \) V of the \( I(U, x) \) curve shown in Fig. 3, is depicted in Fig. 4. If the metallized half \( x < 0 \) of the LAPSL surface was illuminated, a constant photocurrent with an amplitude of about 1 \( \mu \text{A} \) was generated. The amplitude of the photocurrent depended on the thickness of the metal layer. The thicker the metal layer was, the more photons were absorbed or reflected and the fewer charge carriers were generated in the semiconductor substrate. No photocurrent could be measured at naked regions, far away from the metal layer \( x > 0 \). If parts of the uncovered surface adjacent to the metal covered half were illuminated, a photocurrent was flowing due to diffusion of light-generated charge carriers into the metal covered part of the semiconductor substrate. The closer the lateral distance of the point of illumination to the metal layer was, the more charge

<table>
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<tr>
<th>Table 2</th>
<th>Spatial resolution ( r_{\text{bc}}^2 ), calculated for frontside illumination and thick ( (d \gg L) ) semiconductor substrates</th>
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<td>( \lambda_l \ll d ):</td>
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<td>( \lambda_l \gg d ):</td>
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<td>( \lambda_l \ll d ):</td>
<td>( 7/15d^2 )</td>
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 carriers could reach the metal-covered part of the semiconductor substrate and the bigger the photocurrent was. Photocurrents recorded on uncovered regions near the borderline $x = 0$ had a higher amplitude than that recorded on metallized parts $x < 0$, since there was no absorption or reflection at the metal layer.

Correlated to the decay of the maximum photocurrent amplitude $I_{\text{max}}$ with increasing $x$, photocurrent–voltage curves $I(U)$ were shifted along the voltage axis, i.e. the point of inflection $U_{ip}$ of the sigmoidal $I(U)$ curves was shifted to more positive values (see Fig. 5). Plotting the point of inflection $U_{ip}$ vs. $I_{\text{max}}$ yielded an almost linear relation. To further understand these findings, an additional experiment was done, in which photocurrent–voltage curves were recorded at one fixed point $x = \text{const}$ under different illumination power. These data showed the same, almost linear $U_{ip}(I_{\text{max}})$ curve as was observed in Fig. 5. This indicates that the point of inflection $U_{ip}$ of any $I(U)$ curve is directly correlated to maximum photocurrent $I_{\text{max}}$.

To obtain a value for the spatial resolution, the decay of the photocurrent $I(U = \text{const}, x)$ recorded at constant bias voltage on the metal free part of the surface ($x > 0$) was fitted with a mono-exponential function (see Fig. 4). In Fig. 6, the so obtained decay length $l_d$ is plotted vs. the bias voltage $U$. In the case of strong inversion, $l_d$ was found to be almost constant, and depended only weakly on the applied bias voltage. However, this constant part of the decay length $l_d$ was obtained at very negative bias voltages, where also the photocurrent only weakly depends on changes in potential. In contrast, LAPS measurements are usually performed at a bias voltage set to the point of inflection $U_{ip}$, since here, the photocurrent depends maximum on potential changes. Here, the decay length $l_d$, as determined analogously to Fig. 4, is bigger than the value for $l_d$, which has been obtained in strong inversion. This effect suggests that spatial resolution depends on the applied bias voltage. However, alternatively, this effect might be attributed to the shift of the photocurrent–voltage curve, which was caused by the declining amplitude of the photocurrent (see Fig. 5). To test this interpretation, the characteristics of the photocurrent near the point of inflection was analyzed in more detail. For that purpose, the decay length was calculated in an alternative way. To circumnavigate the shift of the $I(U)$ curve, the amplitude of the photocurrent $I_{\text{p}}(U_{ip}(x), x)$ at the point of inflection at each position $x$ was calculated. By fitting $I_{\text{p}}(x)$ in the metal-free part of the surface, the decay length $l_{d,\text{p}}$ was obtained, similar to the decay length $l_d$ that was obtained from the $I(x)$ curves in strong inversion (see Fig. 6). The decay length $l_{d,\text{p}}$ was found to be very similar to the constant decay length $l_d$, obtained in strong inversion. Therefore, the increase in the decay length $l_d$ near the point of inflection is presumably not connected to a reduction in the spatial resolution, but has rather to be considered as an artifact, which is correlated to the shift of the photocurrent–voltage curve. The data further suggest that spatial resolution does not depend on the bias voltage, at least in the regions where photocurrent flows. Both the $l_d$-values, which were obtained for very negative bias voltages, and the value of $l_{d,\text{p}}$, obtained at the point of inflection, are therefore attributed to lateral diffusion of charge carriers parallel to the sensor surface and thus to spatial resolution.

In order to test to which degree the so obtained decay length depends on the maximum amplitude of the pho-

\[
\text{Fig. 3. Photocurrent–voltage } I(U) \text{ curves, recorded at different regions } x \text{ on a LAPS chip with a specific resistance of } 5\text{–}10 \ \Omega \ \text{cm (no. 2, see Table 1). The left half of the surface } (x < 0) \text{ was covered with a thin metal layer, the right half } (x > 0) \text{ was bare and thus not connected to the applied bias voltage. The thick line marks the cross section at constant voltage } U = -8 \ \text{V, which is shown in Fig. 4.}
\]

\[
\text{Fig. 4. Cross-section of the diagram shown in Fig. 3 at constant bias voltage } U = -8 \ \text{V. The } I(x) \text{ curve, which was recorded on the uncovered region of the device, was fitted with a mono-exponential function with decay length } l_d.
\]
Fig. 5. (a) Photocurrent–voltage curves $I(U, x = \text{const})$ (left graph) and their derivatives $dR(U, x = \text{const})/dU$ (right graph), recorded at different positions $x$ of the light pointer. (b) Maximum photocurrent $I_{\text{max}}$, plotted vs. the position of the light pointer $x$. $I_{\text{max}}(x)$ decreases, if the distance $x$ of the light pointer ($P = 1 \text{ mW}$) to the metal-coated part of the substrate (no. 3, see Table 1) is increased. (c) Parallel to the decay of $I_{\text{max}}$, the point of inflection $U_{\text{pi}}$ is shifted to more positive values. (d) $U_{\text{pi}}$ plotted vs. $I_{\text{max}}$. This curve was obtained by combining the data points shown in (b) and (c) by eliminating the $x$-variable.

tocurrent, experiments were done under various illumination power $P$. In the range of $P = 0.05–1 \text{ mW}$, no systematic correlation between the light power and the decay length was observed. Likewise, no dependence of the thickness of the used insulating layers on the decay length was found. To analyze the dependence of the spatial resolution on the specific resistance of the semiconductor substrate, the decay lengths $l_d(U < 0)$ and $l_{d,\text{pi}}$ were determined for all semiconductor substrates described in Table 1 (see Fig. 7). All shown decay lengths represent the mean value of at least 10 different measurements.

The results shown in Fig. 7 indicate that the decay length decreases for low specific resistance. The shortest decay length observed in this study ($l_d = 14 \pm 2 \text{ m}\mu\text{m}$) was

Fig. 6. Decay length $l_d$, which was obtained by fitting the $I(U, x)$ curve at constant voltage $U$ shown in Fig. 5a with a mono-exponential function, plotted vs. the bias voltage $U$ (crosses). The dotted line describes the decay length $l_{d,\text{pi}}$, which was obtained by fitting the decay of the $I_{\text{pi}}(x)$ curve. For very negative voltages $U$, both decay lengths $l_d$ and $l_{d,\text{pi}}$ match.

Fig. 7. Decay length $l_d$, obtained in strong inversion, in dependence of the specific resistance $\rho$ of the silicon substrate. Each data point represents the mean value ± standard deviation from at least 10 measurements. Values for the decay length $l_{d,\text{pi}}$, obtained at the point of inflection, are identical $l_d$ within the error bars.
obtained with a semiconductor substrate with a specific resistance of $\rho = 0.014$ $\Omega$ cm (no. 1). For semiconductor substrate no. 3, which consisted of a thin epi-layer, the measured decay length was $l_d = 17 \pm 3$ $\mu$m, which is significantly smaller than the decay length and which has been obtained for thick semiconductor substrates (nos. 2

Fig. 8. (a) Amplitude of the photocurrent $I$ in strong inversion, plotted vs. the position $x$ of the light pointer, which was scanned across the surface of a LAPS chip with two differently thick metallized halves ($x < 0$: 80 nm NiCr, $x > 0$: 25 nm NiCr). (b) First derivative of the curve shown in (a). The curve is fitted with a Gaussian distribution.
and 4) with similar doping density (no. 2: \( \text{i}_{\text{s}} = 43 \pm 13 \) \( \mu \text{m} \); no. 4: \( \text{i}_{\text{s}} = 38 \pm 4 \, \mu \text{m} \)).

Since measurements of the decay length were restricted by the focus of the light pointer, the size of the light pointer was determined by scanning the light pointer from the thick (80 \( \mu \text{m} \) NiCr) to the thin (25 \( \mu \text{m} \) NiCr)-coated half of a semiconductor surface (\( \rho = 15 \, \Omega \, \text{cm} \)). At fixed bias voltage (\( U = -2.5 \, \text{V} \)), the photocurrent rose from \( \approx 0.3 \) to \( \approx 2.5 \, \mu \text{A} \), as the light pointer crossed the borderline between both parts. The photocurrent–distance curve \( R(x) \) for a fixed bias-voltage was differentiated to calculate the intensity profile of the light pointer, which is assumed to be approximately proportional to \( dR(x)/dx \). This profile was fitted with a Gaussian distribution and the full width at half maximum was considered as the diameter of the light spot (see Fig. 8). The so obtained value \( 2r_L = 7 \, \mu \text{m} \) is in good agreement to microscopy pictures of the light spot.

5. Discussion

The diffusion equation was solved analytically while neglecting the drift term. This is certainly an appropriate model to describe isotropic diffusion of holes in the bulk of the semiconductor. In this, model holes, which eventually reach the surface of the semiconductor, are considered to be sucked into the space charge region and therefore are lost for the further isotropic diffusion process in the bulk. However, although these holes are trapped to the semiconductor surface by the electric field of the space charge region, they still can diffuse parallel to the surface. Since this additional lateral spread of holes was not considered in the theoretical model, obtained values for spatial resolution have to be regarded as lower limit of \( r_{\text{the}} \). This effect mainly has to be taken into account in the case of front illumination with a short penetration depth of the photons, and in the case of very thin semiconductor substrates, where a considerable part of charge carriers is generated directly in the space charge region. Nevertheless, it seems reasonable that due to recombination and scattering at surface states and potential inhomogeneities, lateral diffusion in the space charge region is restricted, and thus the error of the theoretical model can be tolerated.

The spatial resolution \( r_{\text{map}} \), which was determined experimentally by imaging surface potential patterns by other groups, is in acceptable agreement with the results, which have been obtained using the theoretical model (see Table 4). The definition of resolution will stay a complex problem because line/space (L/S) patterns [7] may lead to smaller values than decay curves. The contrast in images of L/S patterns depends both on spatial resolution and on the amplitude of surface potential variations within the L/S pattern. Therefore, the results are not completely comparable. Nevertheless, the theoretical findings of this study and the experimental results also reported by other groups clearly demonstrate that spatial resolution can be improved by using thin semiconductor substrates. As has been reported by Ito [13], spatial resolution can be further improved by laterally structuring the surface of the semiconductor substrates.

In order to quantitatively analyze the experimental results, the features of the employed experimental set-up merit discussion. First, owing to the size of the light pointer (\( 2r_L = 7 \, \mu \text{m} \)), no diffusion lengths shorter than \( \approx 5 \, \mu \text{m} \) could be resolved. Furthermore, it was assumed that the electric field of the space charge region is aligned in \( z \)-direction, perpendicular to the surface of the semiconductor substrate. According to this assumption, only under the metal-covered parts of the surface, a space charge region with static electric field would exist. However, analogously to the field distribution in a plate capacitor, a transverse field will exist at the borderline to the bare part of the surface, and, therefore, the space charge region expands to this part of the semiconductor substrate. This would involve to high values for the measured decay length \( l_d \). In a plate capacitor, the range of the transverse field is certainly smaller than the distance between both plates. Analogously, the lateral expansion of the space charge region (in \( x \)-direction) in the bare part of the semiconductor should not be greater than the extension of the space charge region perpendicular to the surface (in \( z \)-direction). For highly doped silicon substrates, for which the shortest decay length \( l_d \) was measured, the width of the space charge region is \( \approx 100 \pm 400 \, \mu \text{m} [14] \). Hence, the uncertainty in determining \( l_d \) due to transverse field is certainly smaller than the errors caused by the finite size of the light pointer. Finally, a general, inherent limitation of the described experimental set-up has to be considered. In this report, spatial resolution was measured by determining the effective lateral diffusion length \( l_d \) in naked, and therefore unbiased parts of the semiconductor substrate. In actual experiments, under these conditions, no photocurrent would flow. Therefore, a potential improvement would be to determine the effective lateral diffusion

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<td>[7]</td>
<td>300</td>
<td>633</td>
<td>2</td>
<td>&lt;500</td>
<td>–</td>
</tr>
<tr>
<td>[7]</td>
<td>100</td>
<td>633</td>
<td>2</td>
<td>&lt;100</td>
<td>–</td>
</tr>
<tr>
<td>[7]</td>
<td>20</td>
<td>830</td>
<td>5</td>
<td>&lt;10</td>
<td>6–14</td>
</tr>
<tr>
<td>[13]</td>
<td>0.5</td>
<td>532</td>
<td>1</td>
<td>&lt;5</td>
<td>0.14–0.35</td>
</tr>
</tbody>
</table>
length in parts of the semiconductor substrate that are negatively biased.

The experimental results, which have been obtained in this study, suggest that lateral diffusion of light-generated charge carriers decreases with decreasing specific resistance and thus with increasing doping density. Since doping ions may act as scattering centers for free holes and thus reduce the bulk diffusion length, this finding is in good agreement with our theoretical model. A quantitative comparison between the experimentally determined \( l_d \) and the theoretically predicted values \( l_{theo} \) is difficult, since especially for low doping densities the bulk diffusion length is determined rather by the manufacturing process of the semiconductor substrate, than by its specific resistance and thus is not known. However, although spatial resolution can be improved by using highly doped semiconductor substrates, it has to be taken into account that this is connected to a loss in potential sensitivity. In the limiting case, where a semiconductor substrate would be as highly doped that it would behave like a metal, no space charge region would be created and no photocurrent would flow. Therefore, highly doped semiconductor substrates are certainly desirable for obtaining good spatial resolution, but have to be avoided in order to get sufficiently large photocurrents.

Compared to thick semiconductor substrates with similar specific resistance, the measured decay length for a thin semiconductor substrate was reduced (see Fig. 8, substrate nos. 2–4). The potential sensitivity of both thick and thin semiconductor substrates was found to be similar. Therefore, using thinner semiconductor substrates is a much better way than using semiconductor substrates with enhanced doping density in order to obtain better spatial resolution. The best spatial resolution that was obtained for thin semiconductor substrates (no. 3) in this study was \( 17 \pm 3 \, \mu m \). This value is significantly bigger than the value of only a few micrometers, as estimated by the theoretical model. One explanation for this mismatch could be that the assumptions in Eqs. (4) and (5) might not be strictly fulfilled, if the recombination at the surfaces would not be much faster than diffusion. The finite size of the light pointer should not have played a role, since it was significantly smaller than the obtained value for \( l_d \). On the other hand, substrate no. 3 was an epi-structure, which consisted of a thin layer (3 \( \mu m \)) of silicon with high specific resistance (10 \( \Omega \) cm), which was grown on a thick silicon substrate (0.38 mm) with low specific resistance (0.005–0.02 \( \Omega \) cm). It seems likely that, although the light-generated charge carriers have been created only in the thin, first silicon layer of the epi-structure, there may have been further lateral diffusion in the underlying, second and highly doped silicon layer, which might have significantly worsened spatial resolution. This view is somehow equivalent to the assumption that Eq. (5) is not fulfilled. One indication for this explanation is that the spatial resolution of the epi-structure (no. 3: \( 17 \pm 3 \, \mu m \)) was found to be in the same range, as the spatial resolution, which has been determined with a thick semiconductor substrate (no. 1: \( 14 \pm 2 \, \mu m \)) with a specific resistance comparable to that of the second layer of the epi-structure (no. 3: 0.005–0.02 \( \Omega \) cm; no. 1: 0.014 \( \Omega \) cm). This interpretation suggests that spatial resolution should be further improved by using an epi-structure with a first layer with low specific resistance that is only \( \approx 1 \, \mu m \) thin, and of which the second layer has a lower specific resistance like a semiconductor substrate with an inserted modulation doped \( \delta \)-layer. In this way, spatial resolution far better than \( 10 \, \mu m \) should be possible.

Acknowledgements

Parts of this study were supported by BMBF Germany (grant no. 0310845A).

References

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