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A simplified surface photoreflectance measurement system

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Abstract. We present a simple and economical photoreflectance measurement methodology that can easily be adapted to conventional scanning optical microscopes. In this design, the laser source is sine-wave modulated so that the second-harmonic modulation distortion within the optical probe beam before and after reflection off the sample surface can be monitored. The desired photoreflectance measurement, which is taken as the change of reflectance as a result of varying the incident optical power, is then obtained from the change in the ratio of the fundamental and second-harmonic signals. We demonstrate our set-up and technique by measuring the implantation damage in nitrogen-implanted silicon samples.

Keywords: reflectance, laser reflectivity, material surface characterization

1. Introduction

The modulated photoreflectance (PR) technique is a useful material characterization technique, especially for the non-contacting and non-destructive characterization of semiconductor surfaces [1–3]. In conventional modulated photoreflectance systems, a two-beam approach, which simultaneously uses both the pump and the probe beams, is commonly adopted. This design employs a modulated high-power pump beam to induce a localized periodic perturbation of the temperature or carrier concentration in the surface region. Such variations in turn lead to a change in surface refractive index and finally are seen as the PR effect. A second low-power laser beam, which is focused onto the same spot, is used for probing the PR effect due to the pump beam. Although this system can in theory achieve low noise and therefore high sensitivity, the alignment between the pump and the probe beams is quite complicated and requires very high precision. To eliminate this problem, it is desirable to use one laser beam to perform both the pumping and the probing tasks.

The single-beam approach for measuring photoreflectance was first introduced by Wagner and Geiler [4]. In their scheme, a single laser source is split into two portions. The two beams then are modulated by two different frequencies after passing through two acousto-optical modulators. The two beams are finally recombined to form a single beam before impact on the sample. The PR effect, which causes the two frequencies to 'mix' in the reflected beam, is measured at the difference frequency. This technique requires only one laser source. However, the electronics required to modulate and demodulate the optical beam is quite complicated. Furthermore, the fact that the beam has been split into two portions before they are finally recombined to form the probe beam requires very precise alignment in order to avoid signal drift. Suddendorf and Somekh [5] later simplified the system to a 'true' single-beam one so that there is no requirement for precise alignment and thus errors due to the relative drift of the two beams are eliminated. Their design uses a single modulation frequency and a feedback loop for continuously minimizing the second-harmonic content in the input beam. The desired PR information is directly measured by monitoring the second-harmonic content in the reflected beam. Their design has an added advantage of inherent noise suppression due to the fact that all the required signals are derived from the same laser source. However, despite the simplicity of the optical set-up, the feedback electronics requires a number of frequency mixers and amplifiers. A very large feedback loop gain has been used in order to ensure a very low second-harmonic content (120 dB below the fundamental in this case). The measured second-harmonic signal in the reflected beam will then be directly related to the PR effect due to the sample. The requirement of a high loop gain imposes a severe limitation on the high frequency response of the feedback circuit because common amplifiers have quite limited gain–bandwidth products. They removed this limitation conveniently by first mixing the detected signal with a reference second-harmonic signal so that the beat frequency will be at a low frequency. The resultant signal can be amplified with high gain before being fed back to the modulator. This approach is very effective in principle in suppressing the second-harmonic signal at high frequency without having to use high quality amplifiers. It replies primarily on the fact that the second-harmonic signal is negligibly small and

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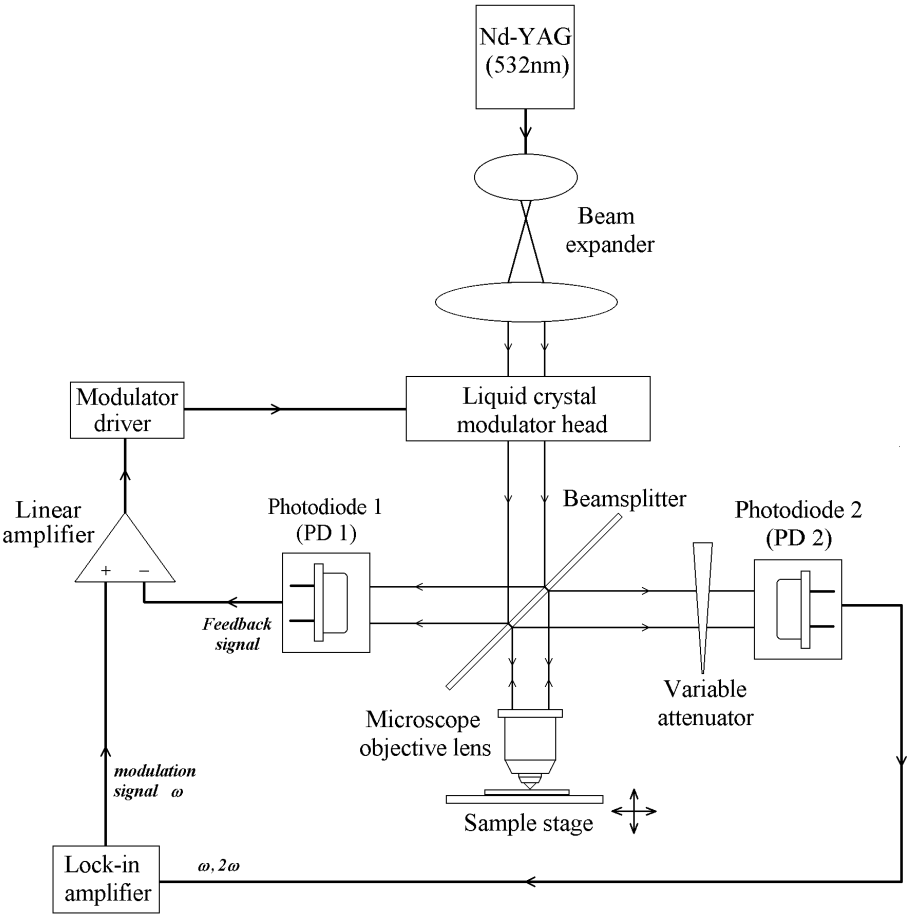

Figure 1. The optical single-beam photoreflectance system.

remains constant throughout the measurement period. Nonlinearity due to the components within the feedback loop, e.g. the amplifiers, the photodiode and the mixers, is not monitored at all. Since the dynamic range that these components have to deal with is quite large because the signal from the PR effect is relatively weak, it is not clear whether one can completely neglect the nonlinearity due to the components within the feedback loop. For this reason we believe that it is better to directly measure the PR effect by monitoring the increase in second-harmonic content after reflection from the sample surface. In this way the measurement process involves the use of one set of electronics and should completely eliminate unwanted common mode signals other than that due to the PR effect.

In this paper, we present a simple single-beam set-up according to the alternative approach we have described above. We use a simple linear amplifier in the feedback loop for removing much of the nonlinearity due to the modulator. We obtain the PR coefficient of the sample by comparing the changes in fundamental and second-harmonic modulation indices before and after reflection from the sample surface. Although a low modulation frequency has been used, which is entirely due to the frequency limitation of the modulator itself, the scheme should present no problem for high frequency operation and is well suited to simple incorporation into existing scanning optical microscopes.

2. Theoretical treatment

The theoretical basis of our system relies on the assumption that the photoreflectance is a linear function of the incident optical density. Suppose that the modulation of the incident beam is described by $I_0[1 + m_1\cos(\omega_m t) + m_2\cos(2\omega_m t)]$. Here I_0 represents the incident optical power, ω_m and $2\omega_m$ are modulation frequencies and m_1 and m_2 are the modulation depths. Any nonlinearity within the incident beam can be taken into account through the incorporation of the $2\omega_m$ term. If we assume that higher order nonlinearity terms are negligible, then the reflectivity of the sample can expressed as $R_0 + \Delta R I_s$, where R_0 denotes the linear reflection coefficient in the absence of optical excitation in the sample and ΔR, which is in mm^2 mW^{-1}, relates the PR effect to the change of reflectivity due to the variable incident optical intensity (I_s), which is in mW mm^{-2}. The intensity of the reflected light, I_r, can be expressed as

$$\begin{aligned}
I_r &= I_s R = I_s(R_0 + \Delta R I_s) \\
&= \left(R_0 I_0 + \Delta R_0 I_0^2 + \frac{\Delta R I_0^2 m_2^2}{2} + \frac{\Delta R I_0^2 m_1^2}{2}\right) \\
&\quad + \left(R_0 I_0 m_1 + 2\Delta R I_0^2 m_1 + \Delta R m_1 m_2 I_0^2\right)\cos(\omega_m t) \\
&\quad + \left(R_0 I_0 m_2 + 2\Delta R I_0^2 m_2 + \frac{\Delta R I_0^2 m_1^2}{2}\right)\cos(\omega_m t) \\
&\quad + \text{higher order terms.} \qquad (1)
\end{aligned}$$

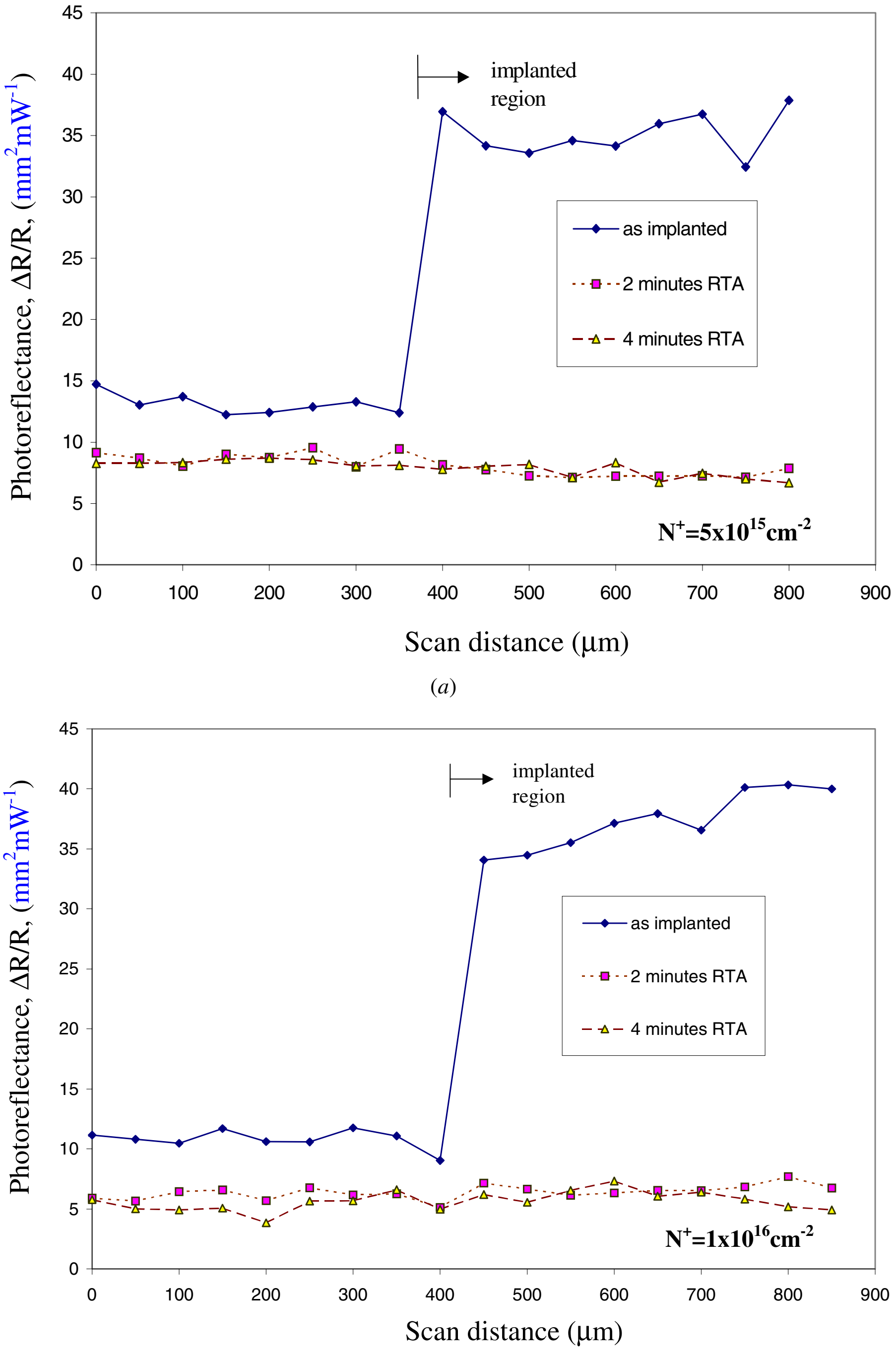

Figure 2. Photoreflectance measurement results on the two nitrogen-implanted samples (5×10^{15} cm^{-2} in (*a*) and 10^{16} cm^{-2} in (*b*) acquired from our set-up, revealing the effects of rapid thermal annealing (RTA) on nitrogen-implanted P-type silicon.

The following equation can be obtained by observing the coefficients of the $\cos(\omega_m t)$ and $\cos(2\omega_m t)$ terms:

$$\frac{S}{F} = \frac{R_0 I_0 m_2 + 2\Delta R I_0^2 m_2 + \Delta R I_0^2 m_1^2/2}{R_0 I_0 m_1 + 2\Delta R I_0^2 m_1 + \Delta R m_1 m_2 I_0^2}. \qquad (2)$$

In equation (2), F and S are respectively the amplitudes of the fundamental and second-harmonic signals in the reflected beam and can be measured by the lock-in technique. Using the relationship $R = R_0 + \Delta R I_s$, the photoreflectance term $\Delta R/R_0$ can be written as

$$\frac{\Delta R}{R_0} = \frac{\left(\frac{S}{F} m_1 - m_2\right)}{I_0\left(\frac{m_1^2}{2} + 2m_2 - (2 + m_2) m_1 \frac{S}{F}\right)}. \qquad (3)$$

This means that, once the measurable quantities, i.e. m_1 and m_2 in the incident beam and F and S in the reflected beam, are known, the value of $\Delta R/R_0$ can be determined.

3. The experimental set-up and results

Figure 1 shows a practical implementation of the proposed technique. Periodic modulation of a 60 mW frequency-doubled Nd:YAG laser is achieved using a liquid crystal optical attenuator (Newport 932-05-V2). Owing to the slow response time inherent to the liquid crystal cell, a low modulation frequency (ω_m) of 20 Hz is used to ensure that one obtains 100% modulation depth. The synthesized modulation signal is obtained from a lock-in amplifier (Stanford Research SR-830). The same lock-in amplifier is also used for capturing the fundamental and second-harmonic signals in the incident and reflected beam via photodetectors PD1 and PD2, respectively. Low-distortion modulation with minimal added second-harmonic content in the optical beam is achieved through use of a linear feedback control loop. The incident optical power, which is monitored by PD1, is continuously compared with the input sine wave through an amplifier. The resultant difference is then used to drive the liquid crystal modulator. With a low modulation frequency of 20 Hz, typical instrumentation amplifiers are well capable of providing the high loop gain required for low-distortion operation.

With regard to the actual PR measurement experiment on real samples, we first performed a baseline assessment of the system to establish the modulation depth of the incident beam, i.e. m_1 and m_2. We placed a variable optical attenuator in front of PD2 and measured the fundamental and second-harmonic signal amplitudes for a wide range of optical intensities impinging upon PD2. An aluminium-coated mirror was used as the reference sample. We assumed that the highly conducting metallic surface has a zero PR coefficient. We found that, for the optical power range of 0.7–10.0 mW arriving at the photo-detector and a detection time constant of 1 s, the maximum variation of the second-harmonic signal, which could also be seen as the gross sensitivity of system, was 3×10^{-5} Hz$^{-1/2}$. The measured sensitivity of the present system is somewhat lower than the value of 10^{-7} Hz$^{-1/2}$ reported by Wagner and Geiler [4]. It should be mentioned that, since the measured photoreflectance value in the present case is indirectly derived from measuring the amplitude of the second-harmonic signal, nonlinearity in the electronics is the main source of unwanted variation in the second-harmonic signal content. The measurement sensitivity was estimated by a simple consideration of the worst possible case, i.e. when the second-harmonic signal was at its maximum amplitude, over a range of optical power levels. These systematic errors are not noise-limited errors and should be reproducible. We believe that the sensitivity of our system can be improved once these systematic errors have been removed through further calibration.

We tested our system on two P-type silicon samples (of nominal sheet resistance 15–20 Ω cm). Only half of the surface of each sample was implanted with 20 kV nitrogen (N^+) ions and the implantation doses were 5×10^{15} and 10^{16} cm^{-2}, respectively. The samples were scanned under the PR measurement probe at a nominal beam diameter of 1.6 μm. As shown in figure 2, the samples clearly exhibit an increase in PR due to the shorter carrier diffusion length associated with the implantation-induced defects [1]. The PR results for the annealed samples are also presented in figure 2. The samples were annealed under nitrogen in a rapid thermal annealing chamber for 2 and 4 min at 850 °C. Clearly, there is a sharp decrease of the PR signal when the ion-implantation-induced damage has been annealed out. Our results are in agreement with those observed by other researchers [1, 2, 5], thus demonstrating the feasibility of the new simplified set-up. Our system should give much more useful characterization information on semiconductor surfaces if a two-dimensional scanning stage is used.

4. Conclusion

We have designed, built and demonstrated a single-beam photoreflectance measurement system for surface characterization of materials. A simple feedback circuit is employed to remove the nonlinear response of the modulator. We have successfully used it to reveal the photoreflectance effect in N^+-implanted silicon. The simplicity of our system makes it well suited to incorporation into existing scanning optical microscopes, for example, the confocal microscopes routinely used in the semiconductor industry.

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