Interference effects in electromodulation spectroscopy applied to GaAs-based structures: A comparison of photoreflectance and contactless electroreflectance

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In this letter, we show that the oscillation features (OFs) usually observed in photoreflectance (PR) spectra of GaAs-based structures grown on the *n*-type GaAs substrate below the GaAs fundamental gap could be eliminated completely by applying the contactless electroreflectance (CER) instead of PR. This finding confirms that the origin of OFs is the modulation of the refractive index in the sample due to the generation of additional carriers by the modulated pump beam. In the case of CER spectroscopy, any additional carriers are not generated during the modulation hence CER spectra are free of OFs. This advantage of CER spectroscopy is very important in investigations of all structures for which OFs are present in PR spectra. In order to illustrate this advantage of CER spectroscopy we show PR and CER spectra measured first for the GaAs epilayer and next for more complicated steplike GaInNAsSb/GaNAs/GaAs quantum well structures. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1873052]

Contactless electromodulation (EM) spectroscopy techniques such as photoreflectance (PR) and contactless electroreflectance (CER) are known to be nondestructive and very powerful techniques for the characterization of semiconductors and their microstructures.[1–4] The basic idea of EM is a very general principle of experimental physics. Instead of measuring the optical reflectance of the material, the derivative with respect to a modulating electric field is evaluated. It leads to sharp, differential-like spectra in the region of interband transitions without uninteresting backgrounds typically found in reflectance spectroscopy.

The CER method utilizes a capacitorlike system with the semitransparent top electrode.[5] A second electrode consisting of a metal strip is separated from the top electrode by an insulating spacer, which is about 0.1 mm larger than the thickness of the sample. The sample is placed between these two capacitor plates. Thus there is nothing in direct contact with the front of the sample. An ac modulating voltage up to 1 kV peak-to-peak is then applied between the two electrodes. In PR instead of directly applying an ac electric field, the sample is perturbed with a chopped laser pump beam. When the laser is on, the photogenerated carriers drift in the built-in electric field, and are captured by surface/interface trap states, thus reducing this field. When the laser is off, the trap occupation, and hence field, is restored. However, PR and CER spectra are not fully equivalent, in general, despite the fact that the modulated parameter for both PR and CER is the built-in electric field. In this letter we show that oscillatory features usually observed for GaAs-based structures grown on the *n*-type GaAs substrate[6,7] are typical only for PR (not for CER). It means that the OFs could be eliminated completely by measuring CER instead of PR. This advantage of CER has never been shown in the literature. In our opinion this observation is very important for the development of CER spectroscopy. Even though CER is less popular than PR spectroscopy, there are many advantages of this technique compared to PR.

The samples used in this study were grown by solid-source molecular beam epitaxy. We selected three samples to present in this paper. The first sample is 0.35 μm thick GaAs epilayer grown on the *n*-type GaAs substrate. The next two samples are steplike GaInNAsSb/GaNAs/GaAs quantum well (QW) structures grown on both *n*-type GaAs and semi-insulating GaAs substrates. The QW structures are composed of 250 nm thick GaAs buffer layer, 50 nm thick GaAs:N layer with the nitrogen concentration of ~0.1%, GaNAs steplike barriers, GaInNAsSb QW, and 50 nm thick GaAs cap layer. The GaInNAsSb/GaNAs QW has a nominal composition of 39% In, 1.7% N, 2% Sb in the GaInNAsSb layer and 2.7% N in the GaNAs barriers. The nominal thickness of the GaNAs steplike barriers and GaInNAsSb QW is 20 nm and 7.5 nm, respectively. Details of the growth conditions can be found in Refs. 8 and 9.

A conventional experimental set-up with a tungsten halogen lamp (150 W) as a probe light source, a 0.55 m monochromator and InGaAs (and Si) *pin* photodiode was applied for by obtaining the PR and CER spectra. For PR, a YAG laser with 532 nm emission was used as the pump beam. The probe and pump beams were defocused to the diameter of 5 mm and the power of the modulated beam was less than 15 mW. In the CER experiment, the top electrode consisted of a transparent conducting ATO layer on quartz, which was kept at a distance of 0.1 mm from the sample surface while the sample itself was fixed on the bottom cuprum electrode. A maximum peak-to-peak alternating voltage of 0.9 kV was applied. Phase sensitive detection of the PR and CER signals was made using a lock-in amplifier.

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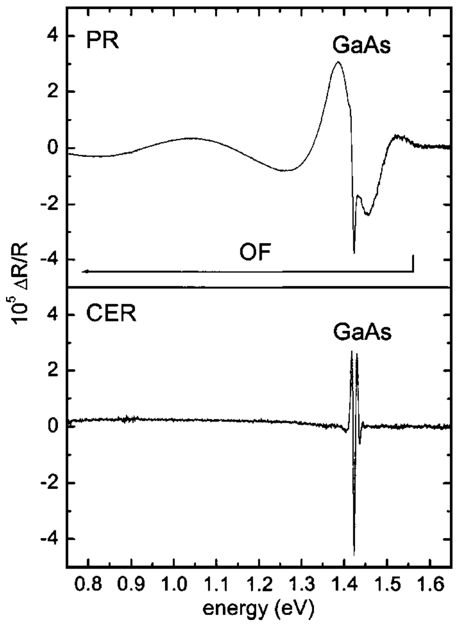

FIG. 1. Room temperature PR and CER spectra of GaAs epilayer grown on the *n*-type GaAs substrate.

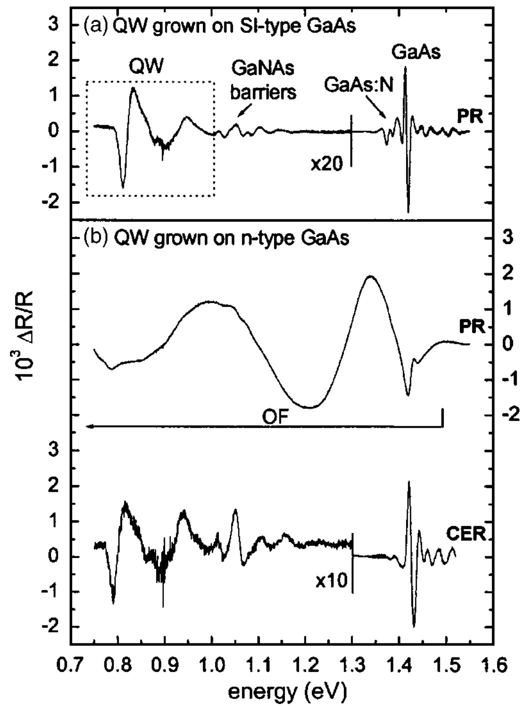

FIG. 2. (a) Room temperature PR spectrum of steplike GaInNAsSb/GaNAs/GaAs QW structure grown on the SI-type GaAs substrate. (b) Room temperature PR and CER spectra of steplike GaInNAsSb/GaNAs/GaAs QW structure grown on the *n*-type GaAs substrate.

Other relevant details of the experimental set-up have been described in Refs. 1 and 4.

Figure 1 shows a comparison of PR and CER spectra obtained for the GaAs epilayer. In the case of PR spectrum besides the GaAs-related feature broad OFs are visible in the range of GaAs transparency. These OFs have been shown to originate from the interference of two light beams reflected from different interfaces of the sample.[6,7] In some cases the observation of such OFs could be useful to determine the thickness of the epilayer grown on the GaAs substrate.[6,7] However, in most cases the presence of OFs complicates the analysis of PR spectra because in order to obtain a maximum amount of information from the PR spectra a fitting procedure must be used to identify each optical transition. It is especially important for GaAs-based structures tailored at long-wavelengths, i.e., N diluted III–V compounds and their QW structures grown on an *n*-type GaAs substrate. As it has been shown in our previous papers the optical transitions could be determined satisfactorily if the amplitude of OFs and PR resonances related to the optical transitions are comparable.[10,11] However, if the amplitude of OFs is much stronger than the amplitude of PR resonances the analysis of optical transitions could be impossible. According to the study of other authors[7,12,13] and our investigations, the ratio of OFs and a PR resonance depends on many factors like: temperature, wavelength, and frequency of modulated beam, the phase of the lock-in detection, and an additional illumination of the sample. For example, the intensity of OFs can be reduced significantly by the application of a shorter wavelength of the pump beam.[13] But, our experience shows that the OFs observed in PR cannot be reduced completely. Such conclusion also results from the principles of PR spectroscopy, i.e., the origin of the OF signal. As has been shown in previous work,[6,7] the origin of OFs is the modulation of the refractive index in the *n*-type GaAs substrate due to the generation of additional carriers by the modulated beam. The refractive index of the substrate can be modulated directly by absorption of the modulated beam in the substrate or indirectly by absorption of the modulated beam in the GaAs epilayer; electron drifts from the epilayer to the epilayer/substrate interface.[6,7] In order to eliminate OFs, the additional carriers, which change the refractive index, have to be eliminated. In CER spectroscopy, addition carriers are not generated. Therefore, CER spectra are free of OFs as seen in Fig. 1. Our finding evidently confirms that OFs are related to the modulation of the refractive index due to the change in the carrier concentration.

PR spectra of steplike QW samples are shown in Figs. 2(a) and 2(b). In the case of the sample shown in Fig. 2(a), steplike GaInNAsSb/GaNAs/GaAs QW structure grown on SI-type GaAs substrate, no OFs are observed. In this case, we can identify very precisely the optical transitions related to absorption in GaInNAsSb/GaNAs QW, GaNAs steplike barriers, the intermediate GaAs:N layer, and GaAs cap and/or buffer layers.[14] As one can see a lot of optical transitions are observed below the GaAs band gap, i.e., in the region of possible OFs. If the OFs appear in the PR spectra most of the information is lost as is seen in Fig. 2(b), for the steplike QW structure grown on the *n*-type GaAs substrate. However, if we apply CER instead of PR we can eliminate OFs completely, as shown in the CER spectrum in Fig. 2(b). Careful analysis of optical transitions for structures grown on *n*-type GaAs substrates is now possible. This advantage of CER spectroscopy could be especially important if we want to perform a comparison of optical and electrical properties of the structure grown on the *n*-type substrate. The application of CER instead of PR is not limited to samples grown on the SI-type substrate. Moreover, in some cases OFs are observed for samples grown on SI-type substrates.[12,15] We have applied the CER spectroscopy for such samples (e.g., samples shown in Ref. 15) and we have not observed any OFs. In our opinion the issue of OFs needs more systematic investigations for a broader family of semiconductors in order to gain a deeper understanding of this phenomenon. We suppose that different kinds of OFs could appear in PR. For example, Ghosh and Arora have observed OFs for CdTe films grown on the Si substrate in both PR and CER.[16] These OFs have completely different behaviors than OFs shown in Refs. 6, 7, 10–13, and 15 and in this paper. So far, we have observed only OFs that are understood within the explanation, which has been proposed by Huang *et al.*[6] and is continued in this paper. Finally we have concluded that if OFs are caused by additional carriers which are generated by the modulated beam, we are able to avoid this problem by measuring CER instead PR.

We suppose that in the case of samples grown on the SI-type substrate, OFs are also possible to be observed if the modulated beam is able to significantly modify the refractive index in the substrate and/or in the layer. In general the refractive index is a function of carrier concentration and its value is different for SI-type and *n*-type GaAs.[17] It could be the reason why the OFs are strong for layers grown on the *n*-type GaAs substrate and almost not observed for layers grown on the SI-type GaAs substrate. In other words, for samples grown on the *n*-type substrate the additional carriers generated by the modulated beam cause different changes in the refractive index of the layer and the substrate while for layers grown on SI-type substrate changes of refractive index for the layer and the substrate are comparable. It is worth underlining that possible OFs observed for samples grown on the SI-type substrate will also be eliminated in CER spectroscopy, because this technique does not generate any additional carriers which are the origin of OFs.

In conclusion, we have shown that OFs usually observed for GaAs-based structures grown on the *n*-type GaAs substrate can be eliminated completely by measurement CER instead of PR. This finding directly confirms that the origin of OFs is the modulation of the refractive index in the sample. CER possesses the advantage in which additional carriers are not generated in the sample and thus the technique is free of OFs. The advantage of CER spectroscopy should influence the development of this technique for the characterization of GaAs-based structures grown on the *n*-type GaAs substrate. We expect that other modulation spectroscopies, like e.g., piezoreflectance, may possess similar advantage in comparison to PR spectroscopy.

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