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Surface photovoltage spectroscopy of pulsed laser deposited undoped ZnSe/n⁺GaAs

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Abstract

We report surface photovoltage (SPV) spectra of ZnSe thin films deposited on n⁺GaAs substrates in the wavelength range of 400–800 nm. In the above bandgap region of ZnSe (below 450 nm), we find that the major contribution to SPV comes from trapping and re-emission from the slow states at the ZnSe surface and ZnSe/GaAs interface. The effect of interference of light on the SPV spectra, has been analysed for subbandgap wavelength excitation of ZnSe (470–800 nm). In spite of the presence of a large number of subbandgap states in ZnSe, the major contribution to SPV in this wavelength range comes from the substrate. The difference in the magnitudes of the SPV between the bare n⁺GaAs and the ZnSe/n⁺GaAs is due to the reduction of surface recombination velocity (SRV) of the minority carriers in n⁺GaAs.

1. Introduction

Surface photovoltage spectroscopy (SPS) has emerged as a powerful contactless technique for the characterization of semiconductor substrates and multilayers [1–4]. This technique has been successfully used for the evaluation of the band-bending at surfaces and interfaces, interface density of states and diffusion length of minority carriers [5]. This technique is primarily based on monitoring the changes in the band-bending at the semiconductor surface and interfaces in the presence of photogenerated carriers. The absorption of photons generates electrons and holes. These carriers are separated from each other because of the presence of an electric field in the space-charge region resulting in a change in the band-bending. Changes in the band-bending can also be observed in semiconductors due to trapping/detrapping of carriers from the traps and the Dember voltage in semi-insulating semiconductors [6, 7]. SPV experiments have been carried out using the Kelvin probe or chopped light geometry. Both these methods have been used for the study of heterostructure interfaces [8, 9].

In the last few years, ZnSe epitaxial layers on GaAs have become quite important as a blue-green semiconductor laser material and as antireflection coatings on GaAs/AlGaAs lasers. The most common substrate used for the growth of multilayers of II–VI compounds is GaAs. In a previous publication, we have shown that pulsed laser deposition technique gives rise to good

epitaxial quality ZnSe layers [10]. The ZnSe/GaAs heterointerface is associated with many properties different from homointerfaces, which have been studied by electrical and optical techniques [11, 12]. In this paper, we present the details of the SPS results of the ZnSe/GaAs heterojunctions in order to understand the nature of the ZnSe epilayer and heterointerface. In the next section, the performed experiments are discussed. A general theory of SPV, which includes both subbandgap and above bandgap illumination, is discussed in section 3. The results and discussion of the results are then presented in sections 4 and 5, respectively.

2. Experimental details

SPS results on ZnSe/n⁺GaAs are reported here. The n⁺GaAs substrates were Te doped with a doping density of 10^{18} cm⁻³. ZnSe films have been grown by pulsed laser deposition. The details of the deposition parameters have been described in an earlier work [10]. Capacitance–voltage (*C–V*) and current–voltage (*I–V*) measurements on ZnSe/n⁺GaAs epilayers have indicated that the ZnSe epilayers are fully depleted of free carriers and are highly resistive. Similar results have also been obtained from room temperature Hall measurements carried out on the ZnSe/SI GaAs epilayers. To understand the mechanism responsible for the generation of surface photovoltage (SPV) inside the ZnSe epilayers, we have also recorded the SPV spectra of bare n⁺GaAs substrate. This wafer has been heated in the same way as during deposition of the ZnSe films so as to control the effects of substrate heating on the SPV spectra of the GaAs substrates.

The SPS measurements have been done in the chopped light geometry in air at room temperature (300 K). A transparent conducting glass (TCG) has been used as a top electrode, which touches the ZnSe epilayer very lightly (soft touch mode) [13]. The samples were mounted on an electrically grounded copper sample holder. A 50 W quartz–tungsten halogen lamp with a 0.25 m Oriel monochromator has been used as the light source. The data have been recorded at 4 nm intervals. The slit widths of the input and the output slits were 500 μm. The system resolution was about 3 nm. Except when otherwise stated, the chopping frequency has been kept at 13 ± 0.5 Hz. The induced ac voltage on the TCG with respect to the grounded copper sample holder was measured using a buffer circuit and lock-in amplifier (EG&G model 7260). The buffer circuit had a very high input impedance ($\sim 10^{12}$ Ω) so that the voltages measured are unaffected by the high input impedance of the MIS structure used in our measurements. The actual value of the SPV signal was obtained by calibrating the voltage on the TCG using a standard voltage source. After the measurements, the observed spectra were corrected for the variation in the intensity of the light across the wavelength range. The SPV spectra for a constant photon flux were analysed throughout this work. The photon flux is kept low in the present study, so as to satisfy the condition of small SPV ($|SPV| < kT/q$). The reflectivity measurements have been carried out at normal incidence on a Shimadzu UV3101PC spectrophotometer.

3. Theory

The origin of the SPV spectra in bulk semiconductors has been examined in detail by many workers [1–6]. SPV in bulk semiconductors results from the separation and redistribution of charge carriers after their generation. In heterostructures, there are depletion regions at the surface and the interface. The SPV contribution in such cases comes from all the space-charge regions that are illuminated by the incident light. The algebraic sum of the band-bending effects in all these regions gives the resultant SPV. The SPV signal δV_s is defined as the difference

of the band-bending at the surface with and without light. Figure 1 shows the band alignment expected in the ZnSe/n⁺GaAs case where the ZnSe film is fully depleted of free carriers. It also shows the various distances that have been used in the expressions. Assuming the back surface to be grounded and solving Poisson's equation, the front surface potential V_s is written in terms of the charge density inside the substrate and the thin film as

$$V_s = - \int_0^L \frac{x\rho(x)}{\varepsilon(x)} dx \quad (1a)$$

$$= - \int_0^W \frac{x\rho_1(x)}{\varepsilon(x)} dx - \int_W^L \frac{x\rho_2(x)}{\varepsilon(x)} dx \quad (1b)$$

where L is the total thickness of the film and the substrate and W is the total thickness which is depleted of free carriers. $\rho_1(x)$ refers to the fixed charges in the regions of the sample that are depleted of free carriers, i.e. in the region 0 to W . Beyond this region, there is no electric field and the excess carriers due to light illumination contribute to the charge density (referred to as $\rho_2(x)$). The second term, which is important for $\hbar\omega > E_g$, was not considered in earlier work [8]. The excess carrier density is zero in the absence of light. Variations in the charge density $\rho_1(x)$ and $\rho_2(x)$ on illumination results in a change in V_s . The contribution of the first term in equation (1b) to the variation of surface potential may be evaluated in the regime of low illumination by the use of calculus of variations [14]. Expressions for the contribution of the diffusion of carriers to the surface voltage can be evaluated by solving the current continuity equation and Poisson's equation. The final expression for SPV is thus written as

$$\begin{aligned} \delta V_s = & \frac{W}{\varepsilon_s} \delta Q_{ex} + \int_0^{W_f} \left(\frac{W}{\varepsilon_s} - \frac{x}{\varepsilon_f} \right) \delta \rho_f(x) dx + \frac{W - W_f}{\varepsilon_s} \delta Q_{int} + \int_{W_f}^W \frac{W - x}{\varepsilon_s} \delta \rho_s(x) dx \\ & + \frac{\Phi \alpha L_p}{n_0 (S^* + D_p/L_p) (1 + \alpha L_p)} (kT/q) \left(\frac{A\mu_n - \mu_p}{\mu_n} \right) \end{aligned} \quad (2)$$

where S^* is the effective SRV, k is the Boltzmann constant, T is the temperature in Kelvin, q is the electronic charge, Φ effective light intensity inside the substrate, α is the absorption coefficient of light in the substrate, L_p is the diffusion length of holes, D_p is the hole diffusion coefficient, μ_n and μ_p the electron and hole mobilities, respectively, δQ_{ex} is the change in the surface charge density with illumination, $\delta \rho_f$ is the change in charge density inside the film on illumination, δQ_{int} is the change in the interface charge density and $\delta \rho_s$ is the change of the charge density in the n⁺GaAs depletion region on illumination. Derivation of the last term and the explanation of the term A is given in the appendix. This expression differs from the expression derived in [5] by the factor $(A^*\mu_n - \mu_p)/\mu_n$ in the last term on the rhs of equation (2). The term involving electron and hole mobility is not present in the expression of [5]. The various terms in equation (2) refer to the various regions in the system, which contribute to SPV. The first term is the contribution from the changes in the surface charge on illumination. The second term is from the changes in the fixed charge density inside the film. The third term is the contribution to SPV from the changes in the interface charge density due to illumination. The fourth term is from the changes in the fixed charge density in the depletion region of the substrate. The last term in equation (2) arises from the diffusion of carriers inside the bulk n⁺GaAs beyond the depletion region and the excess carriers present at the edge of the depletion region. It is important in the n⁺GaAs substrate for illumination above the bandgap. In the case of n⁺GaAs, there is a depletion region next to the film–substrate interface and the SRV is referred to as an effective SRV at the edge of the depletion region. In the text that follows, reference to SRV in n⁺GaAs is actually to the effective SRV of holes in n⁺GaAs

As the light travels inside the thin film, it undergoes successive reflections at the interface and forms standing waves inside the ZnSe epilayer. Figure 2 shows the intensity of the wave

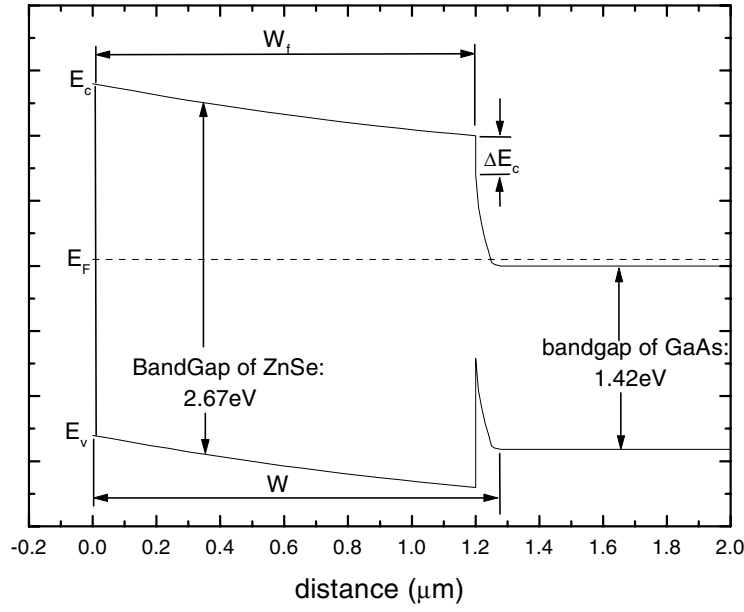


Figure 1. Band diagram of ZnSe/n⁺GaAs obtained by solving Poisson's equation.

as it travels across the film. On adding the amplitudes of the waves for each partial wave as a function of position, we obtain

$$E^+(x) = E_0 \frac{t_{01} \exp(i2\pi n_1 x/\lambda)}{1 - r_{12} r_{10} \exp(i4\pi n_1 W_f/\lambda)} \quad (3a)$$

$$E^-(x) = E_0 \frac{t_{01} r_{12} \exp(i2\pi(2W_f - x)/\lambda)}{1 - r_{12} r_{10} \exp(i4\pi n_1 W_f/\lambda)} \quad (3b)$$

where, E_0 is the electric field of the incident wave, E^+ and E^- are the magnitudes of the electric field of the waves moving in the right-hand and the left-hand sides, respectively and r_{ij} and t_{ij} are the reflection and transmission coefficients for the electromagnetic wave travelling from medium i to j . The total SPV signal from the film is proportional to the intensity of the electric field inside the film ($|E^+(x) + E^-(x)|^2$), integrated over the complete film thickness, which is

$$|E_F(\lambda)|^2 = \int_0^{W_f} E_{\text{film}}^2 dx = \frac{|E_0|^2 |t_{01}|^2 W_f}{G(\lambda)} \left(1 + |r_{12}|^2 + \frac{\text{Re}(r_{12})\lambda}{2\pi n_1 W_f} \left(\sin\left(\frac{4\pi n_1 W_f}{\lambda}\right) - \frac{\text{Im}(r_{12})}{\text{Re}(r_{12})} \left(1 - \cos\left(\frac{4\pi n_1 W_f}{\lambda}\right) \right) \right) \right)$$

with:

$$G(\lambda) = 1 + |r_{12}|^2 |r_{10}|^2 - 2r_{10} \left(\text{Re}(r_{12}) \cos\left(\frac{4\pi n_1 W_f}{\lambda}\right) - \text{Im}(r_{12}) \sin\left(\frac{4\pi n_1 W_f}{\lambda}\right) \right). \quad (4)$$

The SPV signal from the substrate is proportional to the transmitted beam intensity, which is given by the expression:

$$|E_T(\lambda)|^2 = \frac{|E_0|^2 |t_{01}|^2 |t_{12}|^2}{G(\lambda)}. \quad (5)$$

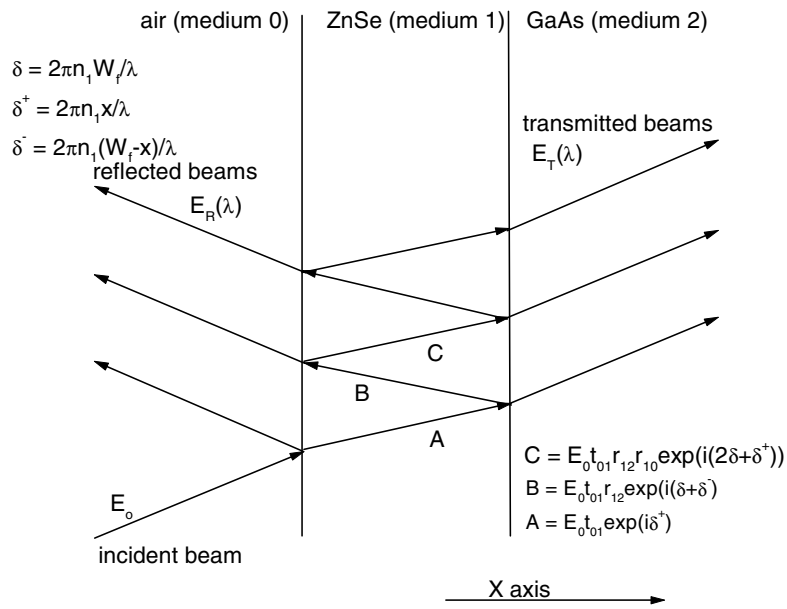


Figure 2. Ray diagram of successive reflections and transmissions that the light undergoes as it passes through the thin film and the substrate.

The photon flux at the substrate (Φ) is proportional to $|E_T(\lambda)|^2$. The reflected beam intensity as a function of the light wavelength λ , is given by:

$$|E_R(\lambda)|^2 = |E_o|^2 \frac{r_{01}^2 + (t_{01}t_{10} - r_{01}r_{10})^2 |r_{12}|^2 + 2r_{01}(t_{01}t_{10} - r_{01}r_{10})H(\lambda)}{G(\lambda)} \quad (6)$$

$$H(\lambda) = \text{Re}(r_{12}) \cos\left(\frac{4\pi n_1 W_f}{\lambda}\right) - \text{Im}(r_{12}) \sin\left(\frac{4\pi n_1 W_f}{\lambda}\right).$$

One can easily show that the wavelength dependence of $|E_F(\lambda)|$, $|E_T(\lambda)|$ and $|E_R(\lambda)|$ is given by the relation: $|E_F(\lambda)| \sim |E_T(\lambda)| \sim (1 - |E_R(\lambda)|)$.

4. Results

SPV magnitude and phase for a constant photon flux, for ZnSe/n⁺GaAs and n⁺GaAs are shown in figures 3(a) and (b). The main observations that are made regarding the SPV spectra are the following: (a) the magnitude of SPV drops down by a factor of six at the band edge of ZnSe and gradually increases with an increase in wavelength of excitation; (b) the phase of the SPV signal makes an abrupt change at the band edge of ZnSe (458–460 nm); (c) periodic maxima and minima are observed in the SPS spectra in the wavelength range of 460–800 nm (the subbandgap region of ZnSe); (d) the magnitude of SPV in the ZnSe subbandgap region is greater in ZnSe/n⁺GaAs as compared to n⁺GaAs by a factor of 5.

5. Discussion

For wavelengths less than 450 nm, i.e. the region greater than the bandgap of ZnSe, the incident light is fully absorbed in about 0.5 μm of the ZnSe film. Hall and CV measurements

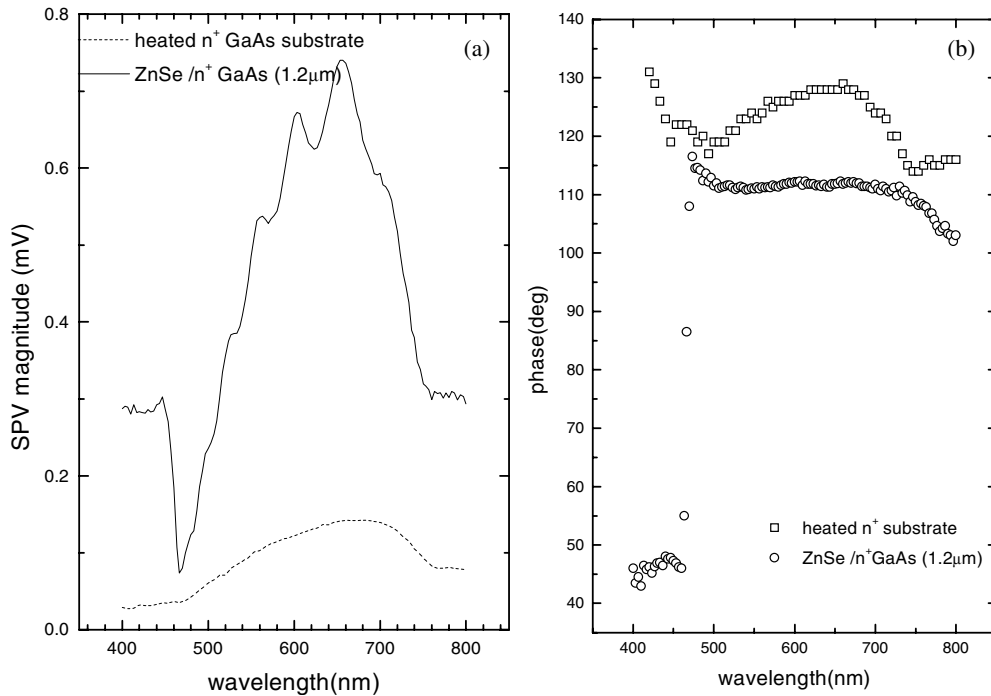


Figure 3. (a) SPV magnitude as a function of wavelength of excitation for ZnSe/n⁺GaAs and n⁺GaAs substrate; (b) SPV phase as a function of wavelength of excitation for ZnSe/n⁺GaAs.

indicate that the ZnSe epilayers are fully depleted of free carriers indicating the presence of large surface and interface charge density [16]. The band-bending for the air/ZnSe interface is about 1 eV [17]. For the evaluation of the conduction band edge inside the film, we solve Poisson's equation with the potential at the surface as 1 eV, bulk density of ionized donors = 10^{14} cm^{-3} and the ΔE_c (conduction band offset between ZnSe and GaAs) of 0.3 eV [16]. The result of the solution using the depletion approximation is shown in figure 1. The dopant density used for the evaluation of the band-bending is only a representative value so that we are in a position to get a fully depleted layer of ZnSe as is observed by our electrical measurements. The free e-h pairs inside ZnSe separate inside the ZnSe film due to the built-in electric field. The holes move to the surface and recombine with the surface states. The electrons would follow the electric field and would reach the n⁺GaAs substrate, as there is no potential barrier for them. In n⁺GaAs, the electrons are the majority carriers and thus the electrons, which reach the substrate from the ZnSe film, do not have a noticeable contribution to SPV. There is no measurable signal above 200 Hz of light chopping frequency for the ZnSe above bandgap excitation. The process of generation of carriers and their separation inside the film due to the presence of an electric field are extremely fast processes and take place within a few picoseconds. Thus the SPV is mainly due to the trapping and re-emission of carriers at the ZnSe surface via states whose response time is in hundreds of milliseconds [6, 15]. The sharp phase change at the band edge ($\sim 460 \text{ nm}$) indicates that there is a change in the process which gives rise to SPV as we go from the above bandgap region to the subbandgap region of ZnSe.

Below the bandgap of ZnSe, modulations are observed in the SPV spectra and the reflectivity spectrum is shown in figure 4. Traces 1–4 in these figures are the calculated

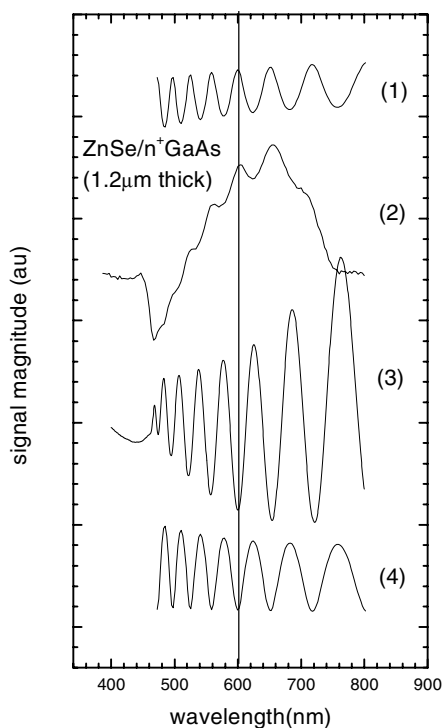


Figure 4. (1) Calculated electric field inside the film; (2) observed SPV magnitude; (3) observed reflectivity curve; (4) calculated reflectivity curve, for ZnSe/n⁺GaAs.

field inside the film, experimentally observed SPV spectrum, experimental reflectivity curve and calculated reflectivity curve, respectively. The transmitted electric field inside GaAs, calculated from equation (5), also has a very similar form to the field inside the thin film. The thickness of the film is determined by fitting the peaks of the reflectivity curves to the calculated reflectivity curve (equation (6)). By this procedure, we find that sample thickness is $1.2 \mu\text{m}$. This thickness value matches very well with the thickness obtained by surface profilometer measurements.

Maxima in the reflectivity intensity correspond to the minima in the SPV magnitude. From the electric field calculations mentioned in the previous section, we find that the peaks in the wavelength of the reflected light (equation (6)) correspond to the minima in wavelengths of both transmitted light intensity (equation (5)) and the electric field intensity in the film (equation (4)). The main point of comparison between the two curves is the position of the maxima and minima in the curves. The difference in the exact shape of the calculated and the measured reflectivity curves may be due to imperfections in the film, leading to absorption below the bandgap, resulting in a finite k value inside the film below the bandgap. This finite value of k is due to the presence of defect states within the energy gap of ZnSe. These have not been taken into account in the refractive index of the film and the substrate. We have taken the wavelength dependence of the refractive index from [17]. The SPV spectrum is compared with the electric field intensity inside the film. The peaks in the SPV spectrum correspond to the position of the peaks in the intensity of the electric field inside the ZnSe epilayer and the substrate. Thus from the oscillations alone, we are unable to determine whether the SPV signal originates from the substrate or the film.

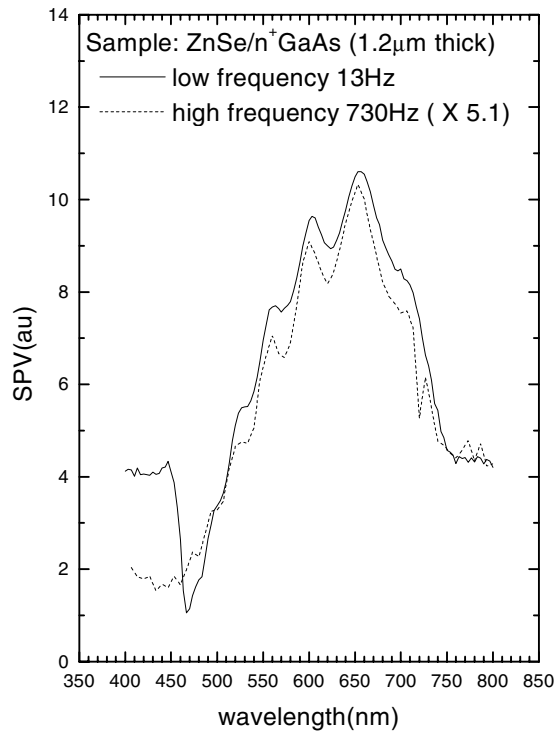


Figure 5. The SPV spectra of ZnSe/n⁺GaAs for 13 and 730 Hz chopping frequency.

For subbandgap illumination, we expect that there would be transitions for electrons from the valence band to the trap levels within the bandgap. There would also be transitions from the trap levels to the conduction band. Both these processes are known to give rise to SPV in CdS [2]. In our case, we know that only slow traps within the bandgap at the surface of ZnSe are responsible for the SPV for excitation wavelengths above the bandgap region of ZnSe. These traps should also be responsible for the SPV for below bandgap illumination. We should thus expect similar frequency dependence for the SPV with below bandgap excitation as with excitations above the bandgap. This is, however, not the case, as we can see in figure 5, where we compare the SPV spectra at 13 and 730 Hz. The high frequency curve has been multiplied by a suitable factor so that the two curves may be compared on the same scale. The two SPV curves are practically the same in the wavelength range of 500–800 nm. This indicates that the major contribution of SPV in this range is not from the slow states inside the ZnSe epilayer or at the ZnSe surface, but from the interface and/or the substrate. This is in spite of the fact that there are states within the energy gap in this energy range as seen from the comparison of the simulated and observed reflectivity profile. We have also recorded the SPV spectra of a 0.55 μm thick film where we find that the magnitude of SPV is very close to the SPV from the 1.2 μm thick film in the wavelength of 500–800 nm. This further confirms that the ZnSe films do not contribute to SPV in this wavelength range. A comparison between the SPV in the same spectral region for the reflectivity corrected SPV spectra of ZnSe/n⁺GaAs at 13 Hz and n⁺GaAs also shows that the two spectra are very identical and have the same gross features. Thus the large enhancement of the SPV signal as compared to the bare substrate is due to the changes at the interface in n⁺GaAs brought about by the deposition of ZnSe.

From equation (2), we find that the changes in GaAs after deposition of ZnSe would be reflected in the third, fourth and the fifth terms. Considering standard values of interface and bulk density of traps, it has been shown that the contribution of the $\delta\rho_s$ term to SPV is much smaller than the δQ_{int} term [18]. It is known that ZnSe deposition on n⁺GaAs passivates the GaAs surface [19]. Thus, there is a fall in the density of states at the n⁺GaAs surface after the deposition of ZnSe. This implies that the δQ_{int} term's contribution will lead to a fall in the magnitude of SPV after ZnSe deposition. This is contrary to our observation. We can explain the enhancement of SPV with ZnSe deposition using the fact that passivation of GaAs surface reduces the magnitude of S^* thereby leading to an increase in the SPV signal in the ZnSe/n⁺GaAs case as compared to bare n⁺GaAs. From the above facts, we conclude that the last term in equation (2) is only responsible for the increase in the SPV signal in ZnSe/n⁺GaAs as compared to bare n⁺GaAs. From the expression of SPV in equation (2), we can estimate the magnitude of the SRV S^* to be of the order of 10^5 cm s^{-1} . There is a reduction in the magnitude of S^* by a factor of five, after the deposition of the ZnSe layer.

6. Conclusion

We have recorded the low frequency SPV spectra of ZnSe/n⁺GaAs and n⁺ GaAs in the chopped light geometry in the wavelength range of 400–800 nm. We observe that above the bandgap of ZnSe, the SPV is mainly dominated by the trapping and re-emission of the electrons and holes at the slow traps within the bandgap at the surface of ZnSe. An analysis of the SPV spectra of both the samples shows that the dominant contribution to SPV in the range of 460–800 nm comes mainly from the substrate. Periodic modulations in the SPV spectra in this wavelength range have been seen for the first time. They have been correlated with the reflectivity spectra and the effect of interference of light inside the film. The difference of the magnitudes of the SPV between the bare n⁺GaAs and the ZnSe/n⁺GaAs is due to the reduction of SRV of the minority carriers in n⁺GaAs. The magnitude of the SRV is of the order of 10^5 cm s^{-1} . There is a reduction of the SRV by a factor of five on the deposition of ZnSe on n⁺GaAs.

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Appendix

The current continuity equation for the electron and the hole current is given by the following equations

$$J_n = q\mu_n n(x)E(x) + qD_n \frac{dn(x)}{dx} \quad (\text{A.1})$$

$$J_p = q\mu_p p(x)E(x) - qD_p \frac{dp(x)}{dx} \quad (\text{A.2})$$

where $p(x)$ and $n(x)$ are the number of electrons and holes in the semiconductor at position x . The number of holes $p(x) = p_0 + \Delta p(x)$. Similarly, $n(x) = n_0 + \Delta n(x)$. Since the incoming photons create electron–hole pairs, we can write in the bulk field free region: $\Delta n(x) = \Delta p(x)$. This is not true in the depletion region (i.e. the region with an electric field) and in the region next to the depletion region inside the field free n⁺GaAs. For the case of upward band-bending, the electrons are swept away from the depletion region into the field free region and

the holes are swept inside the depletion region within a few picoseconds. Thus, we can write: $\Delta n(x) = A(x) \Delta p(x)$ where $A(x) = 1$ inside the bulk n^+ GaAs (i.e. the quasi-equilibrium approximation) and is much greater than 1 close to the boundary of the depletion region. To estimate the SPV contribution from the substrate, we assume $A(x)$ to be a constant A . The total current in the system is zero and so the electric field may be written as:

$$E(x) = \frac{(D_p - AD_n) \frac{d\Delta p(x)}{dx}}{\mu_n(n_0 + A\Delta p(x)) + \mu_p(p_0 + \Delta p(x))}. \quad (\text{A.3})$$

Using the Einstein relationship, we have:

$$E(x) = \left(\frac{kT}{q}\right) \frac{(\mu_p - A\mu_n) \frac{d\Delta p(x)}{dx}}{\mu_n n_0 + \mu_p p_0 + (A\mu_n + \mu_p) \Delta p(x)}. \quad (\text{A.4})$$

We take the excess carriers to be 0 at $x = L$ and take $L \rightarrow \infty$. Thus the potential due to the diffusion of carriers may be written as:

$$V_{\text{spv}} = \int_W^L E(x) dx = \left(\frac{kT}{q}\right) \left(\frac{A\mu_n - \mu_p}{\mu_n + \mu_p}\right) \ln \left[\frac{\mu_n n_0 + \mu_p p_0 + (A\mu_n + \mu_p) \Delta p(W)}{\mu_n n_0 + \mu_p p_0} \right]. \quad (\text{A.5})$$

In the n^+ GaAs case, $n_0 \gg \Delta p_0 \gg p_0$. Thus equation (A.5) may be simplified to give the expression:

$$V_{\text{spv}} = \int_W^L E(x) dx = \left(\frac{A\mu_n - \mu_p}{\mu_n}\right) \left(\frac{kT}{q}\right) \frac{\Delta p(W)}{n_0}. \quad (\text{A.6})$$

The solution of the diffusion equation for the holes with the boundary condition

$$\Delta p(L) = 0 (L \rightarrow \infty) \quad (\text{A.7a})$$

$$\frac{d\Delta p(W)}{dx} = \frac{S^* \Delta p(w)}{D_p} \quad (\text{A.7b})$$

may be written as

$$\Delta p(x) = \frac{\Phi \alpha \tau_p}{\alpha^2 L_p^2 - 1} \left(\frac{S^* + \alpha D_p}{S^* + D_p/L_p} e^{-(x-W)/L_p} - e^{-\alpha(x-W)} \right) \quad (\text{A.8})$$

where $\tau_p = L_p^2/D_p$. The other terms have been discussed in the text. Thus the excess carrier concentration at the edge of the depletion region is given by the expression:

$$\Delta p(W) = \frac{\Phi \alpha L_p}{(S^* + D_p/L_p)(1 + \alpha L_p)}. \quad (\text{A.9})$$

The expression for the contribution to the potential is:

$$V_{\text{spv}} = \left(\frac{A\mu_n - \mu_p}{\mu_n}\right) \left(\frac{kT}{q}\right) \frac{\Phi \alpha L_p}{(S^* + D_p/L_p)(1 + \alpha L_p)n_0}. \quad (\text{A.10})$$

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