Applied Physics Letters

Dynamics of photoreflectance from undoped GaAs

H. Shen, M. Dutta, R. Lux, W. Buchwald, L. Fotiadis et al.

Citation: Appl. Phys. Lett. **59**, 321 (1991); doi: 10.1063/1.105583
View online: http://dx.doi.org/10.1063/1.105583
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v59/i3
Published by the American Institute of Physics.

Dynamics of photoreflectance from undoped GaAs

H. Shen,[a] M. Dutta, R. Lux, W. Buchwald, and L. Fotiadis[a]
U.S. Army Electronics Technology and Devices Laboratory, SLCET-ED, Fort Monmouth, New Jersey 07703-5000

R. N. Sacks
United Technologies Research Center, East Hartford, Connecticut 06108

(Received 18 January 1991; accepted for publication 17 April 1991)

We have studied the time constants involved in photoreflectance from several GaAs surface-intrinsic-n^+ structures. The rise and fall times were determined from digital oscilloscope traces. We find that they depend on the intensity and wavelength of the pump and probe beams. The observed photoreflectance feature does not always follow a single exponential decay. The dependence of rise and fall times on intensity and wavelength of pump and probe beams can be accounted for by a theory based on majority-carrier flow. The characteristic time obtained can be used to determine the potential barrier height.

Photoreflectance (PR)[1–3] is used extensively in the study of semiconductors and semiconductor microstructures.[4] Recently there is growing interest in the use of Franz–Keldysh oscillations (FKO)[2,3,5] to determine Fermi level pinning (V_F) and its changes[6–10] under different conditions. Despite the wide use of PR, its mechanism is not fully understood. Although the major mechanism of PR as being photoinduced modulation of the surface electric field was demonstrated in the early PR studies,[1–3] the dynamics of PR has not been explored in detail. Several experiments[1,11–13] suggested that the mechanism for PR is the modulation of electric field through a recombination of minority carriers with charges in traps (surface, interface, or bulk). The modulation was achieved by a chopped, secondary pump beam (a square wave source), impinging on the sample and creating electron-hole pairs when it is on. These charges were then free to fill traps and modify the electric field strength and abruptly change the built-in electric field. When the pump light was switched off, the electric field strength decayed with a characteristic time corresponding to the emission rate of the traps. In these experiments, the time constant was obtained from the spectrum of PR signal versus chopping frequency.

In this letter, we report a time domain study of the dynamics of PR on several GaAs surface-intrinsic-n^+ (SIN^+) structures.[6,7,14] Our results show that the PR characteristic time constant of these samples is not related to the emission rate of minority carriers from traps, but can be explained by majority-carrier flow from the bulk material annihilating the holes trapped at the surface of the semiconductor.

GaAs SIN^+ structures grown by conventional molecular beam epitaxy (MBE) were used in this study. An undoped GaAs top layer of thickness $d = 500$–2000 Å was grown on an n^+-(100) GaAs substrate with an n^+-doped 1.0-μm-thick GaAs buffer layer. The conduction- and valence-band configuration are schematically shown in Fig. 1. These samples were previously used in the study of Fermi level pinning,[6] which revealed strong Franz–Keldysh oscillations near the fundamental gap of GaAs. The strength of the electric field determined from FKO was used to deduce the surface potential barrier V_m.

In the present room-temperature experiment the lock-in amplifier of a normal PR apparatus was replaced by a data averaging digital oscilloscope. The pump was the 6328 Å He-Ne laser beam chopped by an acousto-optic modulator to provide fast rise and fall times (< 1 μs). The probe beam, from a tungsten lamp and quarter-meter monochromator combination, was set at the two extrema of the PR spectrum, one above the gap at $\lambda_{\text{probe}} = 8730$ Å and the other below the gap at $\lambda_{\text{probe}} = 8930$ Å (see Ref. 6). The power of the two beams were measured by a calibrated power meter. Results from samples with different thicknesses are similar; only the results from the 2000 Å sample will be discussed below.

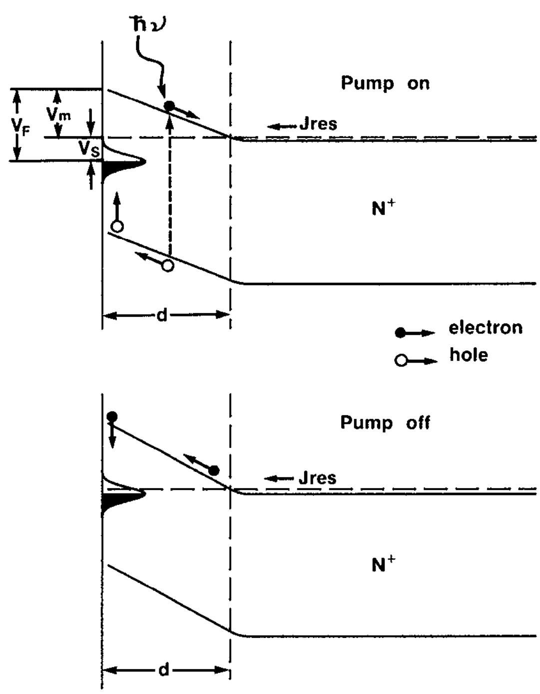

FIG. 1. Schematic energy-band diagram of a GaAs SIN^+ structure with an arbitrary distribution of surface states. Also shown is the carrier flow when pump beam is on (upper) and when pump beam is off (lower).

[a]GEO-Centers, Inc., Lake Hopatcong, NJ 07849. Work performed at US Army ETDL.

 0003-6951/91/280321-03$02.00

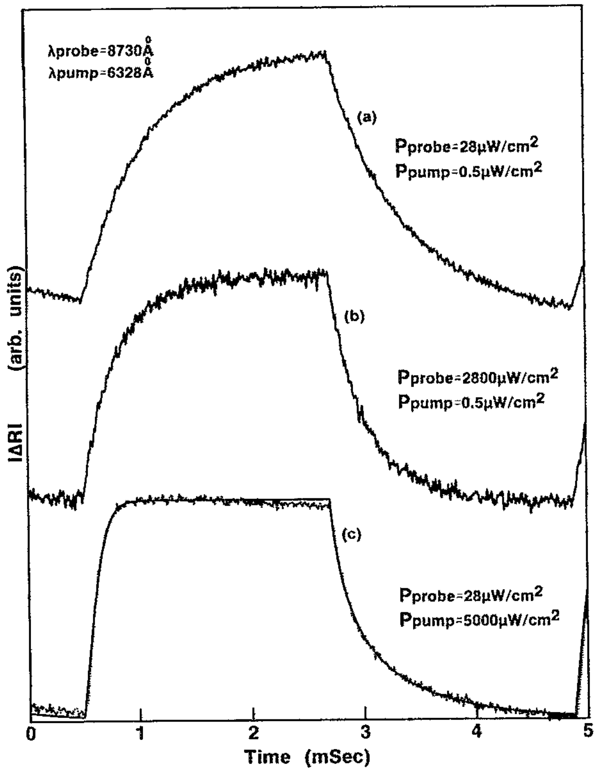

FIG. 2. Photoreflectance signal rise and decay curves from GaAs SIN$^+$ structure at the probe beam wavelength of 8730 Å. The dotted line in C is nonexponential. The solid line in C is a least-squares fit to Eq. (5).

Shown in Figs. 2(a) and 2(b) is the response of the PR signal monitored at $\lambda_{\text{probe}} = 8730$ Å with $P_{\text{probe}} = 28\ \mu$W/cm^2 and $P_{\text{probe}} = 2800\ \mu$W/cm^2, respectively. The pump power was $P_{\text{pump}} = 0.5\ \mu$W/cm^2. Plotted in Fig. 3 is the result at $\lambda_{\text{probe}} = 8930$ Å with the same power as that in Fig. 2(b). The rise and fall times were obtained by a least-squares fit to an exponential decay (not shown). No noticeable deviation from a single exponential decay was found within our signal-to-noise ratio. The rise time is slightly shorter than the fall time, the latter being listed in

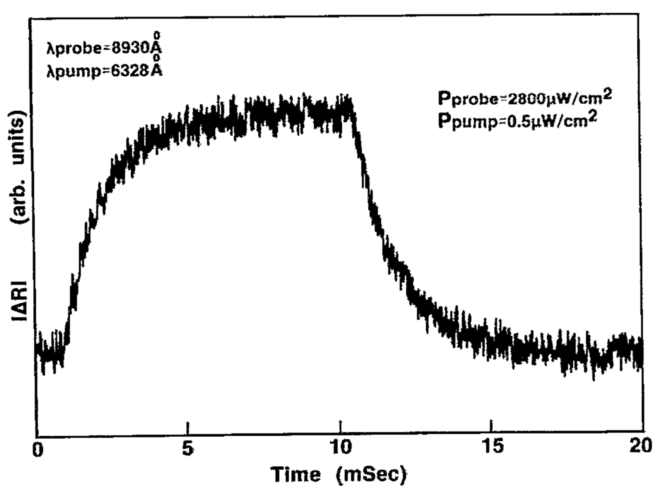

FIG. 3. Photoreflectance signal rise and decay curve from GaAs SIN$^+$ structure at the probe beam wavelength of 8930 Å.

TABLE I. Fall time constants and surface potential barriers measured at different intensity and wavelength of the probe beam. The power density of the probe beam is 0.5 μW/cm^2.

P_{probe} (μW/cm^2)	λ_{probe} (Å)	τ (ms)	V_m^{FKO} (V)	V_m^{Cal} (V)
28	8730	0.70	0.68	0.69
2800	8730	0.33	0.66	0.67
2800	8930	1.44	0.66	0.71

Table I. Also listed in Table I are the potential barrier height V_m^{FKO} measured from FKO in a conventional PR experiment with the same light intensity and the modulation frequency of 480 Hz.[6]

Under small modulation, the strength of PR signal is proportional to the ac electric field derived from the ac photovoltage. Therefore, Figs. 2(a) and 2(b) represent the change of the electric field under optical pump. It is clear that we do not observe the abrupt change of electric field when the pump beam is switched on. In fact, the rise time is approximately equal to the fall time. Thus, it is unlikely that the dynamics of PR are related to a trap state, as it is always energetically favorable for a trap to capture some carriers. Furthermore there is no simple reason why both the capture and emission rates of a trap state (or two or more discrete surface states)[15] depend on both probe intensity and probe wavelength.

The result in Table I can be understood as follows. The top undoped layer, which supplies the PR signal, is sandwiched between the negative charges in the surface states and the positive charges in the thin depleted layer of the n^+ buffer (Fig. 1). The capacitance per unit area is $C=\epsilon\epsilon_0/d$, while the resistance per unit area is $R=(\partial J_{\text{res}}/\partial V_s)^{-1}$. Here J_{res} is the restoring current density[16,17]

$$J_{\text{res}}=J_{\text{st}}[\exp(qV_s/kT)-1], \qquad (1)$$

with V_s the photovoltage, J_{st} the saturation current density, q the electron charge, and k the Boltzmann constant. For our sample, Bethe' s condition[13,14] $F> kT/ql$ is satisfied, where l is the carrier mean free path and F is the electric field. Therefore, the thermionic emission is the dominant contribution to the saturation current, i.e.,

$$J_{\text{st}}=A^{**}T^2\exp(-qV_F/kT), \qquad (2)$$

where $A^{**}=8.0$ A/cm K^2 is the effective Richardson constant and V_F is the surface Fermi level. Thus the time constant for the system is

$$\tau=RC=(\epsilon\epsilon_0/d)(kT/q)(1/A^{**}T^2)\exp(qV_m/kT). \qquad (3)$$

Here we have used $V_m=V_F-V_s$.

In Eq. (3), the time constant depends on the photovoltage, and hence on P_{probe} and λ_{probe}. The calculated barrier heights, V_m^{cal} also listed in Table I, are in good agreement with FKO for measurements at $\lambda_{\text{probe}}=8730$ Å. However, at $\lambda_{\text{probe}}=8930$ Å, V_m^{cal} is significantly larger than V_m^{FKO}. This is due to the small absorption (electroabsorption $\alpha\approx 28$ cm^{-1})[18] and hence low photovoltage at this wavelength which is below the fundamental gap of

GaAs. In fact the calculated potential barrier $V_m^{\rm cal} = 0.71$ V is in good agreement with the result obtained from FKO under a much lower illumination power.[6] In an optical experiment the electric field changes when the photon energy changes. Since the electric field determined in PR is from the FKO observed above the band gap, $V_m^{\rm FKO}$ represents only an average when the probe beam is above the gap.

The dependence of rise and fall time on the pump power is more complicated. The rise time decreases with increasing pump power, as a result of additional induced photovoltage. We have also noticed a small decrease of the fall time. In Fig. 2(c) we show an oscilloscope trace with $P_{\rm pump} = 5$ mW/cm^2 and $P_{\rm probe} = 28$ μW/cm^2. In this case both the rise and the fall processed show a nonexponential decay characteristic. This process can be described by

$$-\frac{dQ(t)}{dt} = -\frac{dV_m(t)C}{dt} = J_{\rm probe} + J_{\rm pump}(t) - J_{\rm res}(t), \tag{4}$$

where $J_{\rm probe}$ and $J_{\rm pump}$ are the probe and pump beam induced photocurrents, and Q is the net positive charge in the depletion layer of n^+ buffer. The solution of Eq. (4) under a square wave pumping is

$$V_s(t) = \begin{cases} V_s^{\rm on} - \Delta V_s f(t - t_{\rm on}, \tau_{\rm on}, \tau_{\rm off}) & \text{Pump on} \\ V_s^{\rm off} + \Delta V_s f(t - t_{\rm off}, \tau_{\rm off}, \tau_{\rm on}) & \text{Pump off} \end{cases} \tag{5}$$

where $V_s^{\rm on}$ ($V_s^{\rm off}$) is the photovoltage after keeping the pump beam on (off) for a long enough time, $\Delta V_s = V^{\rm on} - V^{\rm off}$, $\tau_{\rm on}(\tau_{\rm off})$ is given by Eq. (3) with $V_m = V_F - V_s^{\rm on(off)}$, and

$$f(t,\tau_1,\tau_2) = \ln[1 - (1 - \tau_2/\tau_1) \times \exp(-t/\tau_1)]/\ln(\tau_2/\tau_1). \tag{6}$$

If the pump beam is weak, i.e., $q(V_s^{\rm on} - V_s^{\rm off})/kT \ll 1$ and $\tau_{\rm on} = \tau_{\rm off}$, then Eqs. (5) and 6 can be simplified to a single exponential decay.

Although the effect of probe beam power is not explicitly shown in Eqs. (5) and (6), it does affect the overall dynamics of the process. This effect is involved in Eq. (3) through the dependence of V_m on the photovoltage V_s. We plot in Fig. 2(c) a least-square fit to Eq. (5) with two characteristic times as free parameters. The results are $\tau_{\rm on} = 0.068$ ms and $\tau_{\rm off} = 0.70$ ms. Using Eq. (3) we find that $\tau_{\rm on} = 0.068$ ms corresponds to a potential barrier of 0.62 V.

Our interpretation implies that the surface states which participate in an ac modulation of PR act as recombination centers.[19] They cannot be surface states which only trap one kind of carrier, but must interact with both conduction and valence bands (Fig. 1). When the pump beam is turned on, these surface states discharge electrons by capturing photogenerated holes from the valence band. Also taking place is the competing process of capturing the electrons provided by thermionic emission from the n^+ layer over the built-in potential barrier (i.e., the restoring current). The rate at which these two processes come into steady state gives the characteristic rise times. When the pump light is switched off, the surface states are recharged by capturing electrons from the conduction band again though the restoring current. This recharging will go on until the original electric field is recovered.

In the present experiment we do not see the surface trap states which have been observed in deep level transient spectroscopy (DLTS) measurements. In our experiment the pump duty cycle is larger (50%) and the modulation frequency is higher than in DLTS. The slow trap states cannot follow the pump switching; thus the pump beam creates only an average charging of the states. Although the charges in the trap states contribute to the dc photovoltage, their contribution to the ac PR signal is less important.

In conclusion, we have studied the dynamics of photoreflectance in SIN$^+$ samples. The dependence of rise and fall time on intensity and wavelength of pump and probe beams can be accounted for by a theory based on majority-carrier flow. The characteristic time obtained can be used to determine the potential barrier height. We have demonstrated that the potential barrier height is different when the energy of the probe beam is below and above the fundamental gap of GaAs. We conclude that the surface states responsible for PR modulation in the SIN$^+$ structures are recombination centers. This result is in contrast to the previous models whereby captured holes are always emitted back to the valence band.

The authors would like to thank D. Aspnes for helpful discussions.

[1] J. L. Shay, Phys. Rev. B **2**, 803 (1970).

[2] See, for example, D. E. Aspnes, in *Handbook on Semiconductors*, edited by T. S. Moss (North-Holland, New York, 1980), Vol. 2, p. 109.

[3] See, for example, F. H. Pollak, in *Proceedings of Society of Photooptical Instrumentation Engineers* (SPIE, Bellingham, 1981), Vol. 279, p. 142.

[4] See, for example, O. J. Glembocki and B. V. Shanabrook, in *Proceedings of Society of Photooptical Instrumentation Engineers* (SPIE, Bellingham, 1987), Vol. 794, p. 74.

[5] H. Shen and F. H. Pollak, Phys. Rev. B **42**, 7097 (1990).

[6] H. Shen, M. Dutta, L. Fotiadis, P. G. Newman, R. Moerkirk, W. H. Chang, and R. N. Sacks, Appl. Phys. Lett. **57**, 2118 (1990).

[7] X. Yin, H. M. Chen, F. H. Pollak, Y. Chen, P. A. Montano, P. D. Kirchner, G. D. Pettit, and J. M. Woodall, Appl. Phys. Lett. **58**, 230 (1991).

[8] N. Bottka, D. K. Gaskill, R. S. Sillmon, R. Henry, and R. Glosser, J. Electron. Mater. **17**, 161 (1988).

[9] D. K. Gaskill, N. Bottka, and R. S. Sillmon, J. Vac. Sci. Technol. B **6**, 1497 (1988).

[10] M. Sydor, J. R. Engholm, M. O. Manasreh, C. E. Stutz, L. Liou, and K. R. Evans, Appl. Phys. Lett. **56**, 1769 (1990).

[11] P. M. Amirtharaj, J. J. Kennedy, and P. R. Boyd, J. Vac. Sci. Technol. A **5**, 3184 (1987).

[12] A. Ksendzov, F. H. Pollak, P. M. Amirthraraj, and J. A. Wilson, J. Cryst. Growth **86**, 586 (1988).

[13] H. Shen, Z. Hang, S. H. Pan, F. H. Pollak, and J. M. Woodall, Appl. Phys. Lett. **52**, 2058 (1988).

[14] C. Van Hoff, K. Deneffe, J. De Boeck, D. J. Arent, and G. Borghs, Appl. Phys. Lett. **56**, 608 (1989).

[15] C. J. Spindt and W. E. Spicer, Appl. Phys. Lett. **58**, 1653 (1989).

[16] See, for example, S. M. Sze, in *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), p. 790.

[17] See, for example, E. H. Rhoderick, in *Metal Semiconductor Contacts* (Clarendon, Oxford, 1980).

[18] T. E. Van Eck, L. M. Walpita, W. S. C. Chang, and H. H. Wieder, Appl. Phys. Lett. **48**, 451 (1986).

[19] D. E. Aspnes, Surf. Sci. **132**, 406 (1983).