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Effect of Deep Traps in Carrier Generation and Transport in Undoped InP Wafers*

Zhou Xiaolong[1], Sun Niefeng[2,†], Yang Ruixia[1], Zhang Weiyu[3], Sun Tongnian[2],
Jarasiunas K[4], Sudzius M[4], and Kadys A[4]

(1 *School of Information Engineering, Hebei University of Technology, Tianjin* 300130, *China*)
(2 *National Key Laboratory of ASIC, Hebei Semiconductor Research Institute, Shijiazhuang* 050051, *China*)
(3 *Department of Electromechanical Engineering, Tianjin Agricultural University, Tianjin* 300384, *China*)
(4 *Institute of Materials Science, Vilnius University, LT*-10222, *Vilnius, Lithuania*)

Abstract: Fifty-millimeter undoped indium phosphide (InP) wafers polished on both sides were measured by a ps-degenerate four-wave mixing (FWM) technique. Deep defect related carrier generation, recombination, and decay kinetics and exposure characteristics were measured by time-resolved picosecond FWM at 1064nm at room temperature. The diffraction efficiency of an undoped InP sample as a function of energy is shown for two grating periods. Deep donor defects in undoped InP samples are confirmed by the pronounced effect of space charge electric field on carrier transport.

Key words: InP; ps-degenerate four-wave mixing; deep defect; carrier transport
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1 Introduction

The importance of semiconductors for microelectronics and optoelectronics has stimulated the development of nondestructive techniques for investigating the growth-related photoelectric properties of semi-insulating GaAs, CdTe, and InP crystals[1~4]. The excitation of a semiconductor by a laser pulse and the monitoring of light-induced free-carrier or electro-optic nonlinearities has been a key step in the development of two-wave and four-wave mixing (FWM) techniques. FWM is one of the nonlinear effects that is analyzed extensively in this research. It amounts to the generation of signals at new frequencies due to the nonlinear interaction between two or more input signals. In quantum mechanical terms, FWM occurs when photons from one or two waves are annihilated and new photons are created at different frequencies such that the net energy and momentum are conserved. This interaction requires phase matching conditions between the interacting waves, which are easily satisfied in low dispersion fibers. This paper focuses on the application of FWM for the study of carrier generation, transport, and recombination, as well as defect characterization via light diffraction in InP wafers.

Knowledge of carrier dynamics in semiconductors is a key issue in most technologically important materials. Nonlinear optical techniques of active spectroscopy apply short laser pulses to generate a spatially modulated distribution of nonequilibrium carriers, the so-called transient grating, which temporarily changes the optical properties of a medium. The strong correlation between optical and electrical properties opens the possibility to monitor electrical processes in a semiconductor via carrier dynamics with a picosecond or even sub-picosecond temporal resolution. We demonstrate versatile applications of a light-induced transient grating technique for nondestructive optical monitoring of semiconductor parameters after growth, doping, and irradiation, for the study of defect transformation under illumination or their planar distribution in a wafer[1~3].

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† Corresponding author. Email: nfsun@heinfo.net

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2 Basic principles of the technique

Light diffraction on a light-induced transient free-carrier (FC) grating has been an object of intensive study for the past decade. A particular advantage of this technique is its capability to monitor deep-impurity governed carrier generation, transport and recombination, as it bridges the photoelectric properties of semiconductors with related optical nonlinearities, which are monitored by time-resolved dynamic holography. The key point is the illumination of a semiconductor with a short pulse of a light interference pattern with fringe spacing L for the generation of a spatially-modulated nonequilibrium carrier distribution $N(x) = N_0 + \Delta N\cos(Kx)$ (here N_0 and ΔN are the non-modulated and modulated carrier density along the grating vector $K = 2\pi/\Lambda$). The modulation of electrical properties is duplicated by refractive index n modulation by the value $\Delta n \approx \Delta N$. The delayed probe beam I_P monitors the dynamics of optically induced changes by its diffraction on the grating. The diffraction efficiency of the grating $\eta \approx \Delta n^2$ sensitively reflects the changes in carrier modulation, which decays by diffusion and recombination. Therefore, both the diffusion coefficient D and the carrier lifetime τ_R can be easily determined by monitoring the grating decay time $\tau_G^{-1} = \tau_R^{-1} + K^2 D$ and varying its period. Moreover, recording the transient hologram at the very surface of a semiconductor allows one to determine the surface recombination velocity or investigate carrier dynamics in epitaxial layers, superlattices, or multiple quantum well structures. A proper experimental configuration and modeling of carrier transport allows the determination of the material key parameters, such as trap densities, carrier recombination velocities, diffusion coefficients, and photogenerated carrier concentrations[1~3].

3 Experiment

All 50mm wafers were sliced from ⟨100⟩ undoped InP single crystals which were grown by the liquid encapsulation Czochralski method under high pressure. A high-pressure puller was used for the *in-situ* synthesis and growth of InP crystal. It was originally designed with a phosphorus *in-situ* synthesis facility[5~7]. After compounding, the conventional LEC growth procedure can be carried out. The ranges of carrier concentration are $<1\times10^{16}$ cm^{-3} and mobility >4000cm^2/(V·s). All wafers were polished to a mirror finish on both sides for measurements. The free carrier decay kinetics and exposure characteristics were measured by the time-resolved picosecond degenerate four-wave mixing (DFWM) technique at 1064nm. All measurements were made at 300K in the range of excitations from 0.3 to 10mJ/cm^2 and above, and the grating periods were from 1.85 to 11μm.

4 Results and discussion

The slope coefficient was $2<\gamma<4$ at $\Delta t = 0$ps (Figs. 1(a), (b)), and its increase with intensity points to carrier generation from both impurity band (linear carrier generation, $\gamma = 2$) and interband carrier generation by two-step or two-photon transitions ($\gamma = 4$)[8~10]. The increase of γ with time in "AREA I" points to the presence of effi-

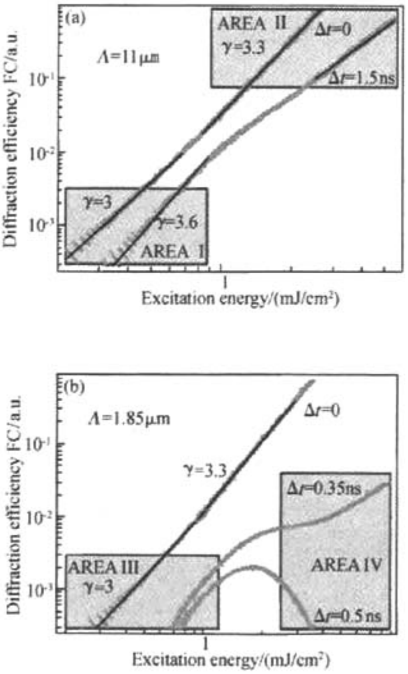

Fig. 1　Diffraction efficiency as a function of energy shown for two grating periods

cient trap filling in the regime of its saturation. The effect is also seen in grating decay dynamics. The significant decrease of γ with time in "AREA II" points to the refilling of optically excited impurities by carriers[8]. The presence of a strong SC field is evidenced by the specifics of exposure characteristics in "AREA III" and "AREA IV"[8]: the SC field increases to ~1mJ/cm^2 ("AREA III") and opposes the diffusive grating decay effectively; at higher excitations ("AREA IV"), the SC field is screened by carrier plasma, and also the charge redistribution in deep impurities is reduced significantly due to linear carrier recombination. This behavior of SC dynamics could be observed directly in DFWM measurements of photorefractive (PR) grating decay dynamics.

The presence of the very fast traps is clearly revealed in FC grating decay kinetics at low excitations by the fast initial decay component. The feature disappears as the traps saturate at higher excitations. Such fast transients in photo carrier dynamics are typically due to the presence of vacancies, which create acceptor-type states[11]. The decrease of the grating decay time from 6.8 to 1.24ns (Fig. 2, $\Lambda = 11\mu m$) is due to the effective carrier recombination to optically excited deep impurity states[8]. The ambipolar diffusion coefficient $D_a \approx 8cm^2/s$ (at $I_0 = 2.4mJ/cm^2$) and the effective recombination time $\tau_R \approx 6ns$ were found from the analysis of angular characteristics. Assuming that $\mu_e \approx 4000cm^2/(V \cdot s)$ and $\Delta n \approx \Delta p$, the hole mobility $\mu_e \approx 170cm^2/(V \cdot s)$ was derived. Analysis of the diffusion coefficient as a function of excitation energy has clearly revealed an n-type crystal photoconductivity[10,11].

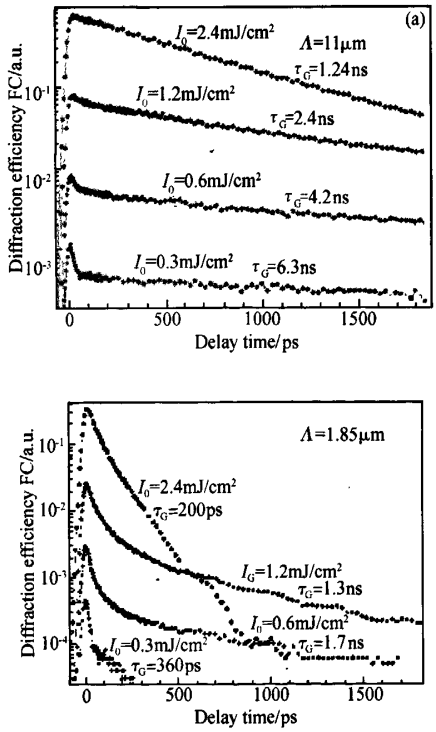

Fig. 2 Diffraction efficiency as a function of time shown for two grating periods

5 Conclusion

We present a novel way to determine the type of dominant carrier photo-excited from deep traps in a photorefractive semiconductor. We applied a four-wave mixing technique to study deep impurity-related carrier photo-excitation and transport peculiarities in undoped bulk InP crystals. All samples showed very efficient trapping of photo carriers until the trapping centers became saturated.

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非掺杂 InP 中深陷阱与载流子的产生和输运的影响*

周晓龙[1,2]　孙聂枫[2,†]　杨瑞霞[1]　张伟玉[3]　孙同年[2]　Jarasiunas K[4]　Sudzius M[4]　Kadys A[4]

(1 河北工业大学信息工程学院，天津　300130)
(2 河北半导体研究所专用集成电路国家重点实验室，石家庄　050051)
(3 天津农学院机电工程系，天津　300384)
(4 Institute of Materials Science, Vilnius University, LT-10222, Vilnius, Lithuania)

摘要： 利用四波混频(FWM)技术对未掺杂双面抛光的InP晶片进行了测试分析.室温下在1064nm用时间分辨皮秒四波混频技术测试了材料的载流子的产生、复合、衰减动力学以及曝光特性等过程.阐明了InP中深陷阱在载流子的产生与输运中的作用,并给予了解释.未掺杂InP样品的衍射效率作为能量函数可用两个光栅周期来表达.未掺杂InP样品中的深施主缺陷也由空间电荷载流子的输运过程来证实.

关键词： 磷化铟；四波混频；深陷阱；载流子输运
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† 通信作者.Email:nfsun@heinfo.net

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