## Double capped heterostructures for carrier confinement



In heterostructures with a thick SLS region (W = several  $\mu$ m) the measured lifetime approaches the bulk lifetime (interface recombination velocity S can be neglected)

## PL and Absorption spectra



PL excitation: Continuous Wave,  $\lambda$ = 0.98 µm, 1 W/cm<sup>2</sup>

The spectra show that PL corresponds to transitions from the bottom of the conduction band to the top of the first valence subband C-V1; C-V2 in the absorption spectrum denotes transitions from the top of the second valence subband to the bottom of the conduction band.

# Time resolved Photoluminescence (TRPL) Scope LN InSb or MCT detector Scope LN InSb or MCT detector BW = 200 MHz A = 1064 nm Vertication Pulsed Excitation Contraction

Assuming that SLS region represents a p-type material with equilibrium hole carrier concentration  $p_0$  assuming equal excess carrier concentrations of electrons and holes

$$\Delta n = \Delta p \quad \text{one can write the following} \qquad I_{PL}(t) \propto \frac{B}{\phi} \left( p_o + \Delta p(t) \right) \Delta n(t) = \frac{B}{\phi} \left( p_o + \Delta n(t) \right) \Delta n(t)$$

Here *B* - radiative recombination constant,  $\phi$  - photon recycling factor The TRPL approach requires multiplication of the PL decay constant  $\tau_{PL}$  by a numerical coefficient between 1 and 2 to be determined experimentally from dependence  $I_{PL}$  on excitation energy. The latter defines the excess carrier concentration  $\Delta n$ . Two asymptotic cases can be considered:

Case 1: 
$$\Delta n(t) \ll p_o \implies I_{PL}(t) \propto \frac{Bp_o}{\phi} \Delta n(t) \implies \tau_{\Delta n} = \tau_{PL}$$
  
Case 2:  $\Delta n(t) \gg p_o \implies I_{PL}(t) \propto \frac{B}{\phi} \Delta n^2(t) \implies \tau_{\Delta n} = 2 \times \tau_{PL}$ 

#### Time-resolved PL decays T = 77 K



The excitation was gradually lowered until the PL decay becomes independent on excitation (in PL tails). The excitation level of 2.3 nJ with excitation area of  $3.4 \times 10^{-3}$  cm<sup>2</sup> corresponds to the excitation flux density of  $3.6 \times 10^{12}$  photons/cm<sup>2</sup>. The initial excess carrier concentration was estimated to be  $2.5 \times 10^{16}$  cm<sup>-3</sup>. The PL decay constant (42 ns) was determined in the PL tail.

The inset shows the dependence of the peak PL intensity on excitation energy. The quadratic dependence indicates that the excess carrier concentration was above the background doping level (case 2).

The carrier lifetime (84 ns) was determined by doubling the PL decay constant.

# **Optical Modulation Response (OMR)**



The carrier lifetime is determined from the cut-off frequency (-3 dB point) of the PL frequency response to steady-state excitation  $G_0$  with sinwave modulation  $G_1$ .

Measurement of PL response with narrow-band (BW < 1Hz) amplification has been improved the Signal-to-Noise ratio that was traded for considerable reduction of excess carrier concentration. Direct measurements for SLS materials at the excitation in mid  $10^{15}$ /cm<sup>3</sup> level has been demonstrated. Measurements at lower (~ $10^{13}$ /cm<sup>3</sup>) excitation levels are possible (in progress).

Due to narrow-band amplification the PL response is linear on excess carrier concentration, therefore for the carrier lifetime no need in multiplication of the PL time constant by a coefficient between 1 and 2!

# **Optical Modulation Response**



The inset shows dependences on steady-state excitation power of both the inverse decay constant and the low-frequency PL response.

Measurement of PL decay constant versus excitation  $1/\tau$  (G<sub>0</sub>) is informative for determination of minority carrier lifetime  $\tau_0$  in the limit G<sub>0</sub>  $\rightarrow$  0. With OMR method the carrier lifetime at ZERO EXCITATION can be obtained.

The OMR method allows determination of the background carrier concentration in PL samples. (no specially-designed Hall samples needed!). The type of carriers in PL samples (electrons or holes) 10<sup>8</sup> can be identified with cyclotron resonance data.

A rapid increase of the PL response with excitation showed that the background carrier oncentration was below the minimum excess carrier concentration at a 2 mW power level. It was estimated to be  $3.5 \times 10^{15}$  cm<sup>-3</sup> (the excitation area was  $1.5 \times 10^{-3}$  cm<sup>-2</sup>).

The minority carrier lifetimes of 80 ns was found for undoped short-period SLS structures for the 3-5  $\mu$ m wavelength region. The current research effort is focused on study of carrier lifetime in SLS structures for photodetectors on both 3-5 and 9-12  $\mu$ m wavelength ranges.