Reply to "Comment on 'Radiative recombination processes of the many-body states in multiple quantum wells' "

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In the preceding Comment, Hillmer, Hansmann, and Forchel discussed possible mechanisms for the spatial expansion of a photodegenerated electron-hole plasma (EHP) in quantum wells. Although not the major topic of our paper [Phys. Rev. B **42**, 2893 (1990)], we agree that excitonic and EHP lateral transport depends strongly on temperature, carrier density, and heterostructure configuration. Our recent results on $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ multiple quantum wells on InP substrate support the idea that wave-guided reabsorption and reemission of the luminescence is responsible for the observed light transport along the crystal surface.

We have recently observed that considerable changes occur in the electron-hole-plasma (EHP) luminescence detected at large distances from the center of the excited spot in GaAs quantum wells at 10 K.[1] Despite the fact that this was not the major result of our work, Hillmer *et al.* address several interesting remarks in their comment on the spatial expansion of photogenerated EHP in quantum wells. They show that excitonic and EHP lateral transport strongly depend on temperature, carrier density, and heterostructure configuration, thus needing a comprehensive and complex treatment.[2] However, most of the data of Hillmer *et al.* do not apply directly to the conditions of our experiments. In fact, as stated by the authors, the description of the EHP transport at high carrier density and very low temperature [point (ii) of the second section of the comment] is complicated by the fact that diffusion,[3,4] thermodiffusion,[5,6] phonon wind, and ballistic transport[7] have not yet been included in a comprehensive theoretical model. Other effects like excitonic transport and EHP transport at higher temperatures have no great relevance for the case under investigation.

An interesting result of the Hillmer *et al.* comment is the strong increase of the ambipolar diffusivity in high-density EHP (Fig. 2). In fact, even a diffusivity coefficient of the order of 10^4 $cm^2 s^{-1}$ (correspondig to a carrier density of the order of 10^{13} cm^{-2} at 100 K in Fig. 2) results in a diffusion length of the order of 20 μm with the observed carrier lifetime. This is in agreement with theoretical[8] and experimental determinations[3,4] and is by far too small to account for our observations. The drift term in Eq. (4) of Ref. 1 can therefore be considered only as a phenomenological approximation to describe the large space distribution of the luminescence. A similar model has been already used by Hillmer *et al.*[9] and by Tsen and Sankey,[10] although the inclusion of proper boundary conditions demonstrated that the driftlike term can be removed.[2] We therefore believe that the comment of Hillmer *et al.* indicates that no EHP lateral transport process can be invoked to explain the presence of intense luminescence at distances of the order of hundreds micrometers from the center of the excited spot. Hence, according to Hillmer *et al.*, the observed light transport along the crystal surface can be due to reabsorption and reemission of the waveguided luminescence in the optically confined cavity. Measurements similar to those reported in Ref. 1 performed on $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ multiple quantum wells grown on InP substrates confirm that luminescence can be observed up to 400 μm away from the spot center.[11] This result supports the conclusion of Hillmer *et al.* In fact, in these heterostructures the transparent InP substrate acts like a natural reflector layer providing some optical confinement of the luminescence. In light of these considerations, further work should be done to elucidate the effects of the EHP expansion and of the luminescence propagation in highly excited quantum wells.

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[1]R. Cingolani, K. Ploog, A. Cingolani, C. Moro, and M. Ferrara, Phys. Rev. B **42**, 2893 (1990).
[2]G. Mahler, T. Kuhn, A. Forchel, and H. Hillmer, in *Optical Non-Linearities and Bistabilities in Semiconductors,* edited by H. Haug (Academic, New York, 1987); H. Hillmer, A. Forchel, T. Kuhn, G. Mahler, and H. P. Meier, Phys. Rev. B **43**, 13 992 (1991).
[3]H. Hillmer, A. Forchel, S. Hansmann, E. Lopez, and G. Weimann, Solid-State Electron. **31**, 485 (1988).
[4]K. T. Tsen, O. F. Sankey, G. Halama, Shu-Chen Y. Tsen, and H. Morkoç, Phys. Rev. B **39**, 6276 (1989).
[5]K. T. Tsen and H. Morkoç, Phys. Rev. B **34**, 6018 (1986).

[6]T. Kuhn and G. Mahler, Phys. Rev. B **35**, 2827 (1987).
[7]F. M. Steranka and J. P. Wolfe, Phys. Rev. B **34**, 1014 (1986).
[8]T. Held, T. Kuhn, and G. Mahler, Phys. Rev. B **41**, 5144 (1990).
[9]H. Hillmer, G. Mayer, A. Forchel, K. S. Löchner, and E. Bauser, Appl. Phys. Lett. **49**, 948 (1986).
[10]K. T. Tsen and O. F. Sankey, Phys. Rev. B **37**, 4321 (1988).
[11]C. Moro, M. Ferrara, R. Cingolani, Y. H. Zhang, and K. Ploog, J. Appl. Phys. (to be published).