

Lee *et al.* Reply: Despite extensive investigation, little is still known about the physical mechanisms responsible for quantum dot (QD) formation in II-VI semiconductor systems, especially when compared to their group-IV or III-V counterparts. However, the distinct chemical and microscopic features characteristic of the various materials make these diverse systems rather exciting to study and compare. We therefore welcome the Comment by Kratzert *et al.* [1] that sheds new light on the CdSe island formation on ZnSe. The method used by them—*in situ* ultrahigh vacuum atomic force microscopy (AFM)—provides valuable information that was not accessible before: it allows one to probe the dynamics of QD formation without external influences (such as the influence of the atmosphere), and it offers minimum delay between QD formations and their characterization. Specifically, and in contrast with our findings [2], these new results do not manifest room temperature ripening of CdSe islands. These new observations, combined with a number of other results recently reported (see below), suggest the existence of three distinct island types:

(A) Formation of uniform islands of sizes between 30–100 nm, and of 6 to 20 nm height, that ripen at room temperature, has been reported on the ZnSe surface *without* the deposition of CdSe [3–5]. This is rather surprising, since it is believed that the origin of *uniform* islands is the relaxation of the strain energy, which comes from the mismatch between the substrate and the deposited material. In contrast, submonolayer islands and mounds seen in *homoepitaxy* have a rather wide size distribution [6].

(B) The islands reported from *in situ* observations by Kratzert *et al.* [1] have diameters of about 30 nm and the typical height is between 1.5 and 3.5 nm, clearly smaller than the type-A islands discussed above. Furthermore, these islands *do not ripen* at room temperature.

(C) The third type of islands [7–9], observed on CdSe/ZnSe samples after they were exposed to air, has a diameter of about 35 to 40 nm and a height of about 15 to 20 nm at their formation, and they do ripen at room temperature [2,10]. Thus these islands have approximately the same size as the type-A islands, much larger in volume than the type-B islands.

The existence of the three island types underscores the complexity of the problem regarding island formation in II-VI systems. The main question is that of the origin of these complex island types. A possible explanation has been suggested by Smathers *et al.* [5], proposing that the composition of the type-A islands in SeO₂, resulting from oxidation of the surface after exposure to air. While detailed experimental confirmation of this picture is still lacking, one can take this hypothesis farther in order to explain the origin of the three island types. The type-B islands, grown and observed in vacuum, are indeed CdSe quantum dots, and they appear to be stable at room temperature. This picture would suggest, however, that the type-C islands may also be the result of the oxida-

tion process. If this is the case, the presence of Cd should not be the primary factor determining the characteristics of type-C islands. This is further supported by the observation of larger islands (reminiscent in characteristics to the type-C islands) coexisting with the type-B islands, after the samples have been exposed to air [1].

One difficulty with this picture is that some investigators [8], including ourselves [7,10], have observed type-C island formation *only* on specimens on which a layer of CdSe has been deposited (see Fig. 1 in Ref. [10]). It is this feature that originally caused us to ascribe the identity of the islands as CdSe or CdZnSe, although we recognize that their real composition is now in question.

The hypothesis of the three island types presented above, although attractive, offers a number of open questions before it can be accepted. (1) The mechanism responsible for the agglomeration of SeO₂ into *uniform* islands is far from being understood: Is this mechanism identical to that which is responsible for QD formation (i.e., strain-relaxation driven) or is it surface-tension driven (which, however, could not explain the remarkable uniformity of the islands at their formation seen for both type-A [4,5] and type-C [2,8,9] islands)? (2) While it is clear that type-A and type-C islands do ripen, we do not know much about the stability of the type-B islands. The very question of the existence of stable dislocation-free islands is an issue of central interest, much discussed in the literature [11].

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- [1] P.R. Kratzert, M. Rabe, and F. Henneberger, preceding Comment, Phys. Rev. Lett. **83**, 239 (1999).
- [2] S. Lee *et al.*, Phys. Rev. Lett. **81**, 3479 (1998).
- [3] D. Hommel *et al.*, Phys. Status Solidi (b) **202**, 835 (1997).
- [4] M. Rabe, M. Lowisch, F. Kreller, and F. Henneberger, Phys. Status Solidi (b) **202**, 817 (1997).
- [5] J.B. Smathers, E. Kneedler, B.R. Bennet, and B.T. Jonker, Appl. Phys. Lett. **72**, 1238 (1998).
- [6] A.-L. Barabási and H.E. Stanley, *Fractal Concepts in Surface Growth* (Cambridge University Press, Cambridge, England, 1995).
- [7] S.H. Xin *et al.*, Appl. Phys. Lett. **69**, 3884 (1996).
- [8] H.-C. Ko *et al.*, Appl. Phys. Lett. **70**, 3278 (1997).
- [9] E. Kurtz *et al.*, J. Cryst. Growth **184/185**, 242 (1998).
- [10] J. Merz, S. Lee, and J.K. Furdyna, J. Cryst. Growth **184/185**, 228 (1998).
- [11] F.M. Ross, J. Tersoff, and R.M. Tromp, Phys. Rev. Lett. **80**, 984 (1998); G. Medeiros-Ribeiro *et al.*, Science **279**, 353 (1998); I. Daruka and A.-L. Barabási, Phys. Rev. Lett. **79**, 3708 (1997).