Synthesis of group IV nanostructures for single-photon avalanche diode detectors

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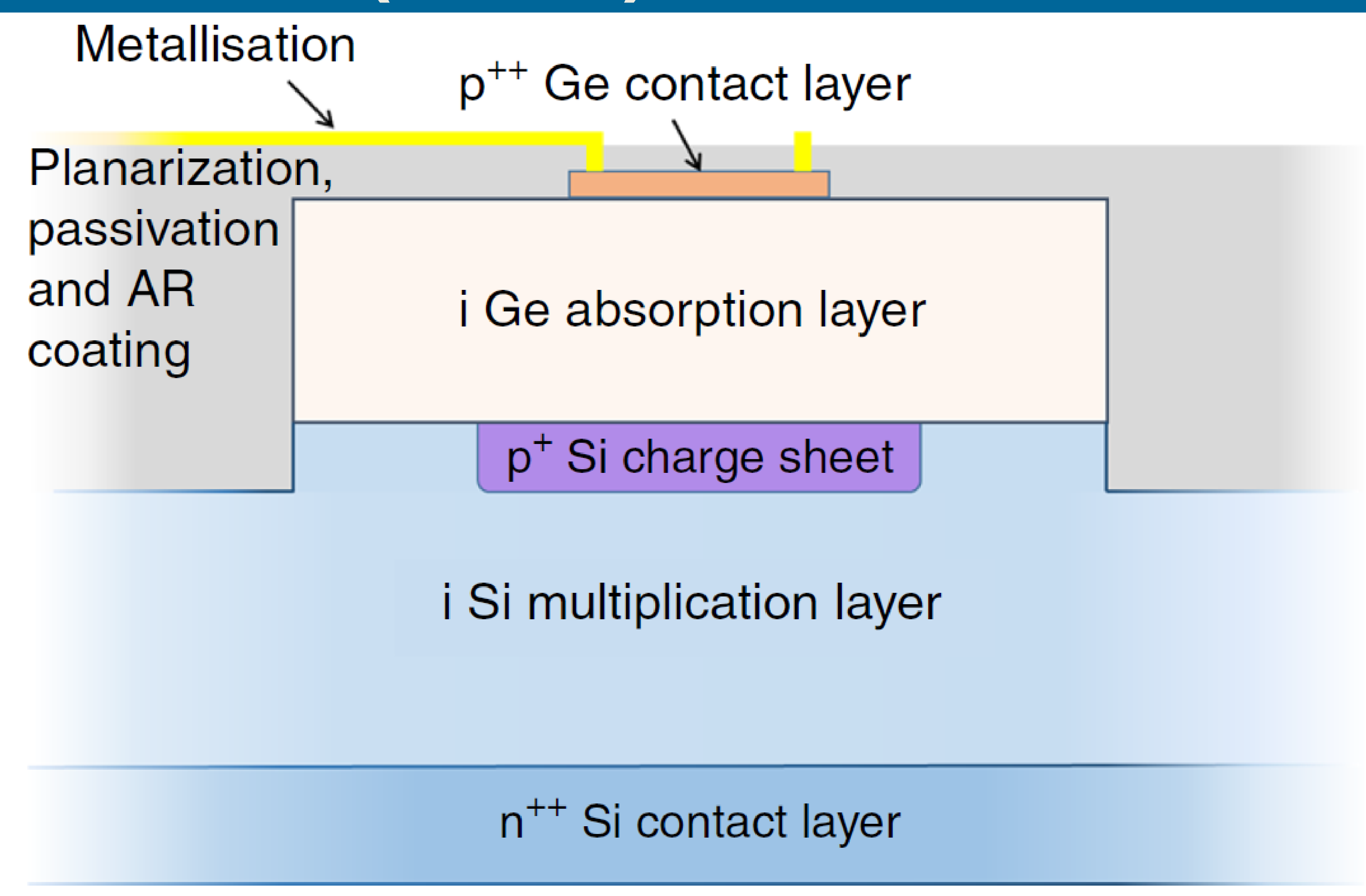
Single-photon avalanche diode detectors (SPAD)

- **Single-photon avalanche diode (SPAD)** are solid-state single-photon detectors capable of capturing single photons with very high timing resolution, the order of a few tens of picoseconds thanks to the impact ionization mechanism (avalanche multiplication) and the digital nature of its output. **Their performance is still needed to be improved** in terms of fill factor (ratio of photon-sensitive area to total area), dark count rate (the rate of spurious pulses due to thermal generation, trap-assisted thermal generation, trap-assisted tunneling, and band-to-band tunneling), photon detection probability (probability that an impinging photon triggers a pulse), timing jitter (uncertainty between actual and measured photon arrival time), afterpulsing probability (probability that an avalanche causes false counts due to traps), etc. *[Vines // Nature Comm, 2019,* ***10****:1086.]*

- **Group IV nanostructures (Si, Ge) are perspective candidates for creation of single-photon avalanche diodes (SPADs)**



Lattice Mismatch and Critical Size of 2D-3D Transition

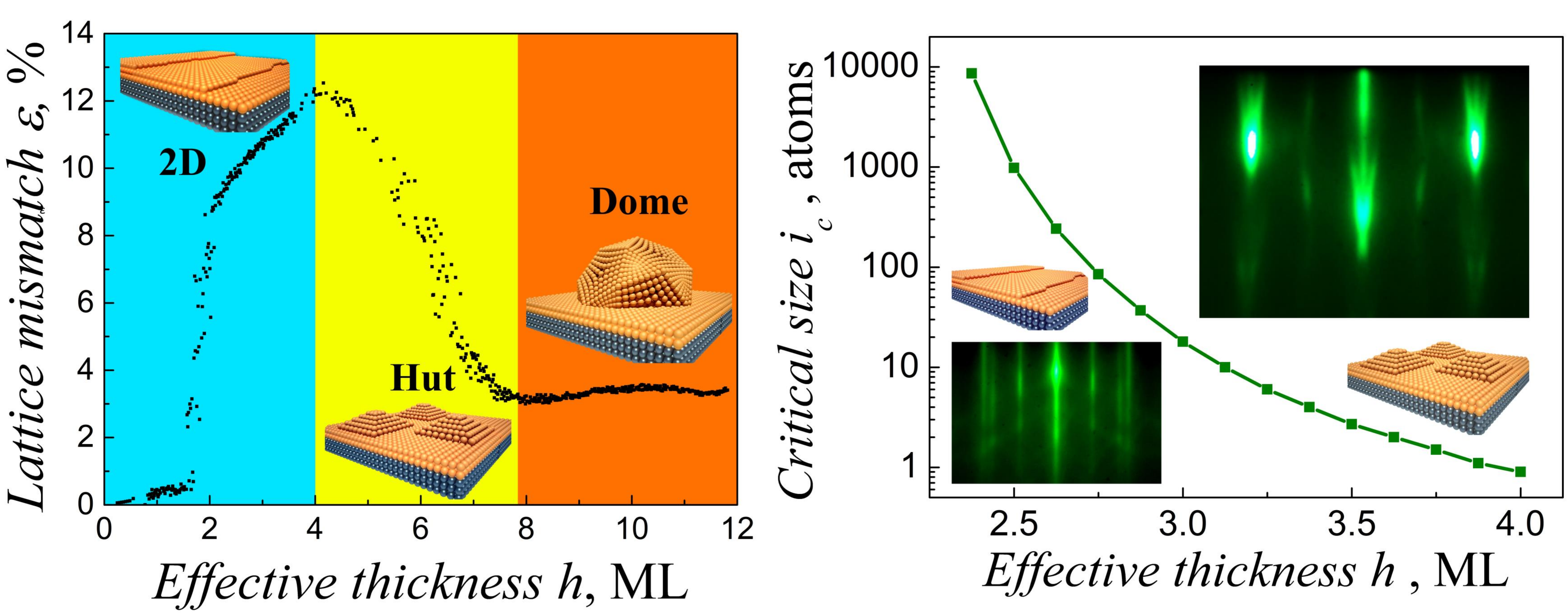


Figure 1. Dependencies of the lattice mismatch between the deposited **germanium layer and silicon substrate** and critical size of an island on the effective thickness of the deposited material (**T = 450 °C**).

Insets: growth modes for each range of thicknesses and diffraction patterns corresponding to the formation of 2D layer and hut-clusters.

Evolution of Epitaxial Quantum Dots Formed by Stranski–Krastanow Growth

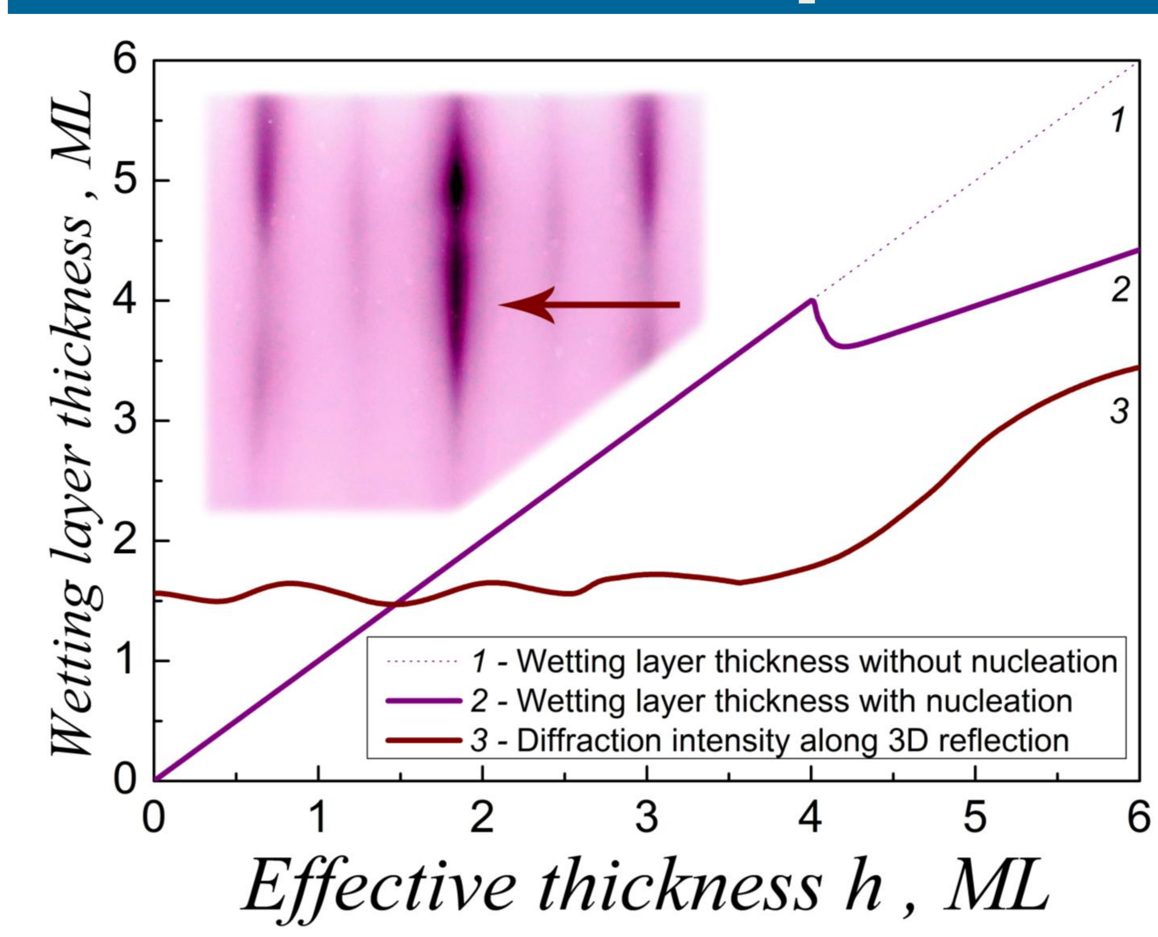


Figure 2. Thickness of the germanium wetting layer and intensity profile (arbitrary units) of the diffraction pattern for the growth temperature **T = 500 °C** and germanium deposition rate **V = 0.03 ML/s**.

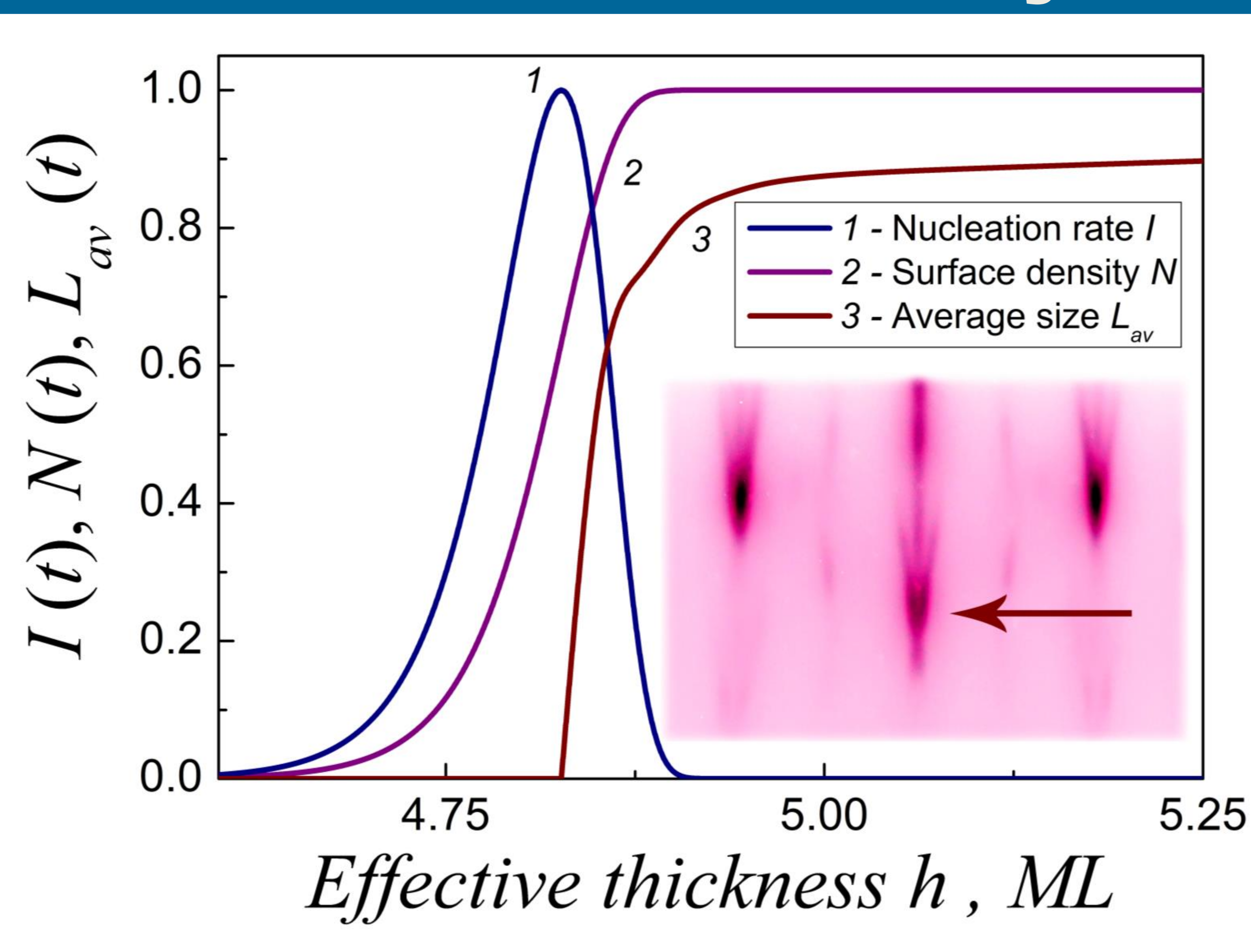


Figure 3. Thickness dependences of normalized values of islands nucleation rate (*1*), surface density (*2*) and average size of QDs (*3*).
Insets: diffraction patterns in [110] azimuth for the effective thicknesses **h = 1.0** and **5.0 ML**.

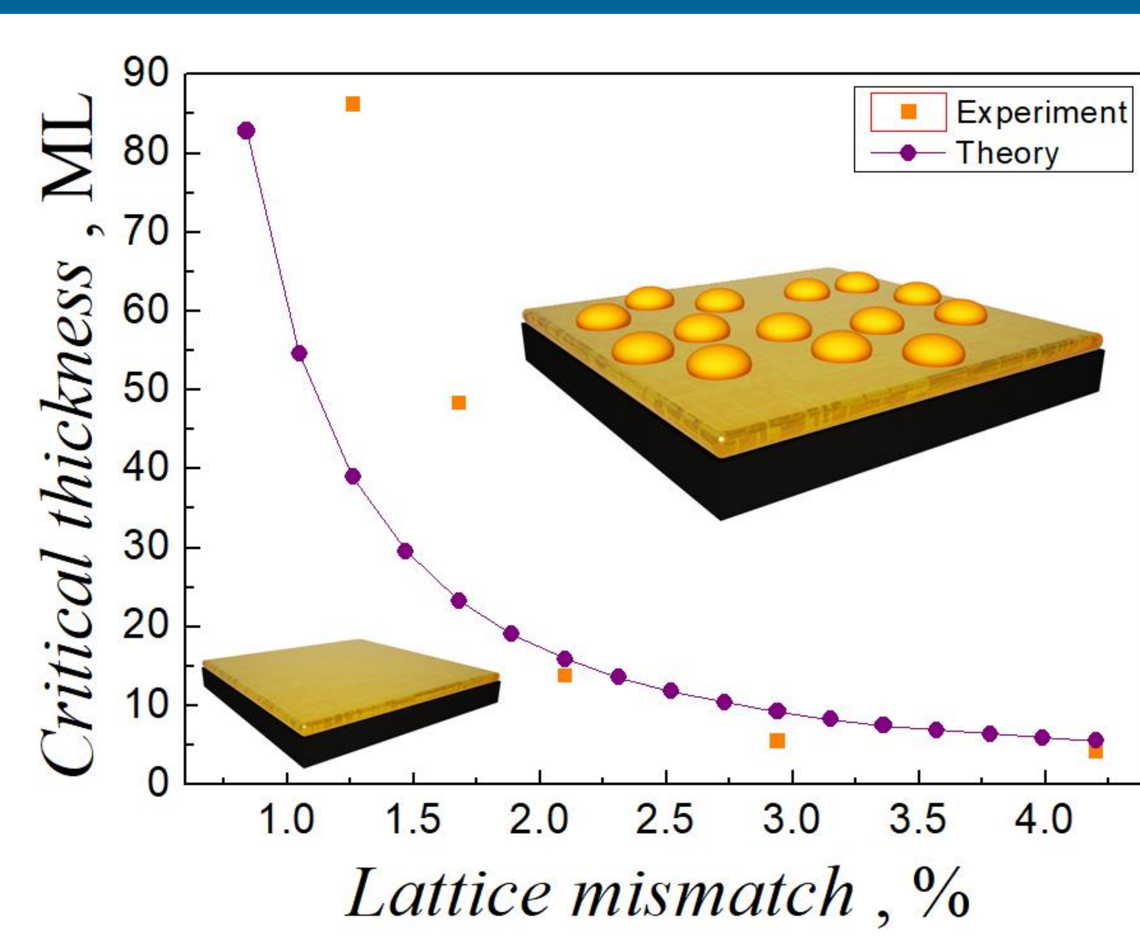


Figure 4. Dependence of the critical thickness of transition from 2D to 3D growth on lattice mismatch for the growth temperatures **T = 400 °C** (theory and experiment in **Ge_xSi_{1-x}/Si system**).

Conclusions

- **Recent progress in the synthesis and implementation of single-photon avalanche detectors based on group IV nanostructures and technological possibilities of improvement of their operating characteristics are reviewed.**
- **Generalized kinetic model of nucleation and growth of 2D layers and 3D islands by all three possible mechanisms is proposed. Dependencies of the structures parameters on the synthesis conditions are obtained. The developed model allows one to evaluate not only equilibrium values of system with quantum dots (their average size and surface density), but also principally non-equilibrium parameters such as islands nucleation rate, size distribution function and its time evolution.**
- **Ways to control the properties of obtained 2D and 0D nanostructures for nanoelectronics and photonics (including single-photon avalanche photodetectors for quantum communication technology) are proposed.**