# Radiation Effects in Low Dimensional Semiconductor Structures

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***Abstract* — The paper presents a survey of effects occurring in Si-Ge and III-V quantum dots, quantum wells, quantum wires and superlattices upon electron and proton irradiation as well as upon ion implantation. The important issue of the radiation hardness is treated in detail. It is shown that QD-based devices can withstand much higher radiation fluences than corresponding 2D and bulk structures. The physical mechanisms of this phenomenon are discussed. Coherent amorphization of superlattices and its relation to the ion-induced intermixing are considered. Examples of the application of particle irradiation to the device technology, especially, self-organized creation of nanopatterns and ion-beam synthesis of embedded nanocrystals, are given.**

***Index Terms* — quantum size semiconductor structures, radiation hardness, radiation technology, ion beam synthesis, embedded nanocrystals.**

## I. INTRODUCTION

The tolerance of materials and devices to radiation-induced defects (radiation defects, RDs) is of crucial importance in atomic energy and space applications. In a nuclear reactor, the samples are exposed to neutrons and gamma-quanta. The space-radiation environment accompanying most useful orbits consists of electrons (energies up to ~7 MeV), protons (energies extending to hundreds of MeV) and small amounts of low energy heavy ions [1]. Besides, the creation of RDs is a collateral effect in ion implantation that is a well-established technique of materials modification. With the onrushing advent of quantum-size semiconductor structures (QSSS), the studies of RDs in them rapidly grow in importance.

To approach the problem of radiation damage, one needs knowledge on the creation, transformation, and annihilation processes of RDs in bulk materials including alloys. Whereas these processes in Si are well understood, the information concerning Ge, GaAs and InP is much less detailed. The worst situation is to be stated for the other III-V compounds and alloys, leave alone the II-VI semiconductors. [2,3] Then one has to establish which layer (or layers) in a concrete, probably very complicated, structure predominantly determines the device parameters degradation. And finally, the role of the Fermi level, heterointerfaces and strain in the defect evolution and defect reactions, the mutual influence of the adjacent layers, and the impact of the quantum confinement on the structure and properties of local defects, which are already known from the studies of the corresponding bulk semiconductors, have to be elucidated.

On the other hand, particle irradiation helps us to learn a lot about, e.g., diffusion processes in QSSs and allows developing novel technological processes of micro-, nano- and optoelectronics. So, the ion beam synthesis of magnetic nanoclusters in semiconductors and oxides is at present a subject of topical interest.

## II. RADIATION HARDNESS

The term “radiation hardness” describes the ability of a structure to withstand the deteriorating action of ionising radiation. In semiconductors, irradiation creates radiation defects that act as non-radiative recombination centres limiting the photoluminescence (PL) and electroluminescence (EL) intensity. An enhanced radiation hardness of the PL and EL in thin-layer Si/Ge superlattices (SLs) as compared to Si/Ge quantum wells (QWs) and to bulk Si has been found [4] (see also Fig. 1). The following model has been proposed to explain the observed effect. When Si is irradiated with 3-4 MeV electrons at room temperature, most of the stable RDs are formed after long-range migration of the primary RDs, i.e. vacancies and self-interstitials, by subsequent interaction and formation of complexes with impurities. At doping levels above ~$10^{17}$ $cm^{-3}$ each primary defect is captured by an impurity atom [5]. An analogous picture may basically be assumed for bulk Ge. Hence, even for an impurity concentration as high as $10^{19}$ $cm^{-3}$ the mean migration length of a primary defect to form a non-radiative centre is much longer than that to reach an interface in a short-period SL (a few Ångströms). The interfaces act as sinks and annihilation centres for the mobile primary RDs, thus leading to a lower concentration of non-radiative centres than in the bulk material.

The influence of proton irradiation on the PL of self-assembled InAs/InP quantum wires (QWRs) and QWs that show PL emission at similar wavelengths has recently been performed [6]. The proton irradiation leads to an extinction of the PL intensity both in QWR and QW samples. However, the QWRs tend to exhibit higher radiation hardness, especially at low temperatures and upon just above-bandgap excitation.

The increased tolerance of defects is one of the most important promises of the quantum dot (QD) nanotechnology [7]. For In(Ga)As/GaAs QDs, irradiation with electrons has indeed been found to quench the PL

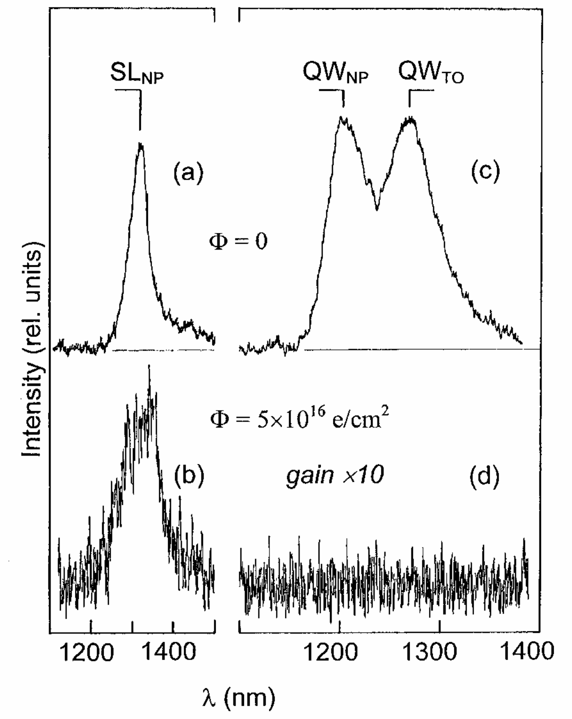

**Figure 1.** EL spectra of a $Si_6Ge_4$ SL and a $Ge_2Si_{20}Ge_2$ QW prior to (a, c) and after (b, d) irradiation with $5\times10^{16}$ $cm^{-2}$ of 3-4 MeV electrons. The lower indices mean the number of atomic monolayers $T_{meas}$ = 4.2 K. SL and QW are characteristic luminescence bands of the SL and QW, respectively. The NP and TO indices refer to no-phonon transitions and their TO-replica, respectively. [17]

intensity about one order of magnitude more slowly than in comparable QW structures [8]. The radiation hardness of the PL against damage due to proton irradiation [9–11] and manganese ion implantation [12] as well as against defects created by an argon ion plasma [13] has also proven to be greater for QDs than for QWs. It has been found that the defect-related recombination in the QDs is indeed weaker than in the QWs [8]. Such property is advantageous for active layers in matrix materials with a high number of structural defects such as GaAs on Si [14–16]. The reduced interaction with defects also appears promising for the improvement of the lifetime of nitride and II-VI lasers.

Time-resolved PL and PL excitation (PLE) measurements allowed a deeper insight into the excitation and recombination processes inside the QDs [10,11]. It has been concluded that the ground state of the exciton localized in a QD is unaffected by defects, at least at moderate irradiation doses, and that the loss of carriers occurs from the excited states.

The above-mentioned facts bring up an important question. Do stable point defects created by atomic displacements at room temperature (RT) exist inside the In(Ga)As QDs? In fact, their existence has never been proven. Since the primary defects are mobile at RT in GaAs (see, e.g., [18–20]) and, certainly, in InAs, it is very likely that they are captured at the interfaces (cf. Ref. [4]). This “self-purification” has later been shown [21] to be an intrinsic property of defects in semiconductor nanocrystals, for the formation energies of defects increase as the size of the nanocrystal decreases.

The improved radiation hardness of QD structures is reflected in a superior performance of irradiated QD lasers as compared to QW ones [22-24]. Enhanced radiation hardness of the electrical properties of the InGaAs/GaAs QD structures upon ion implantation [25] and that of the PL of the Ge/Si QDs upon proton irradiation [26] has been shown, too. There are many other examples of enhanced defect tolerance of the low-dimensional structures. So, e.g., nanostructuring leads to one order of magnitude enhancement of radiation hardness against high-energy heavy ion bombardment in GaN layers [27].

## III. COHERENT AMORPHIZATION OF SUPERLATTICES

Most crystalline materials can be rendered amorphous upon ion bombardment. However, the critical ion fluences needed for the amorphization of different materials vary by orders of magnitude. It is well known that the critical fluence of amorphization of Si is one order of magnitude higher than that of Ge. [28,29] However, the damage kinetics in $Si_{1-x}Ge_x$ alloys for $x > 0.4$ is very similar to that of pure Ge [30]. The difference of the amorphization behaviour between GaAs and AlAs is even much larger [31]. Hence, a selective amorphization of (rather thick) individual layers was usually observed upon ion implantation into multilayer structures such as the SiGe/Si and AlAs/GaAs SLs [28,32].

A quite opposite result has been obtained by us using the Rutherford backscattering (RBS) and high-resolution cross-sectional transmission electron microscopy (HR XTEM) on short-period $Si_6Ge_4$ and $Si_9Ge_6$ SLs: the Si and Ge layers in the SLs were amorphized simultaneously at one and the same fluence that coincided with the critical fluence of bulk Ge [33,34] (see Fig. 2). We assumed that this coherent amorphization of the different layers in a SL can only occur

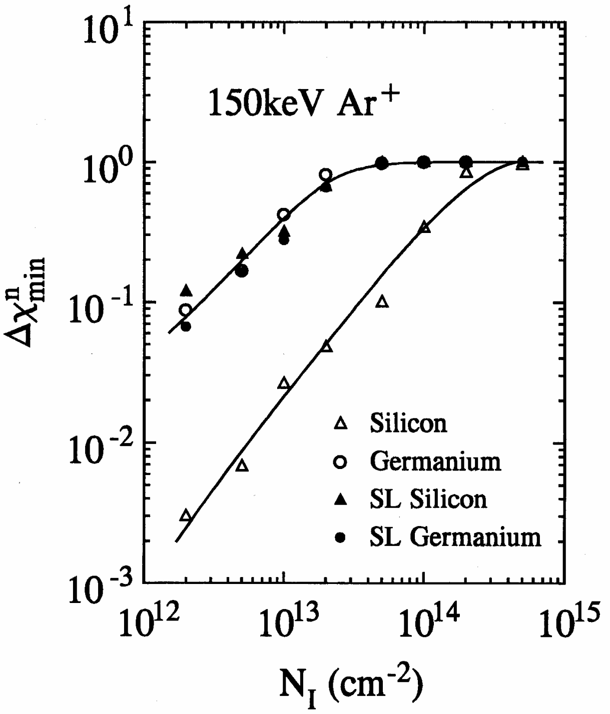

**Figure 2.** Normalized minimum RBS yield (reflecting the relative amount of damage) for the pure crystalline Si and Ge as well as that for the Si and Ge layers in a $Si_9Ge_6$ SL plotted vs. the 150 keV Ar+ ion fluence. [33]

if the SL period (which is only 1.4 or 2.2 nm in the investigated SLs) is shorter than the typical dimension of the individual damage clusters originating from the collision cascades induced by the primary recoil atoms.

As it is impossible to grow structurally perfect Si/Ge SLs with arbitrarily thick layers, AlAs/GaAs SLs with different periods along with $Al_xGa_{1-x}As$ alloys with $x$ ranging from 0 to 1 were implanted to check this idea [35]. (AlAs cannot actually be amorphized by implantation at room temperature, so the implantations and RBS measurements were done at cryogenic temperatures without intermediate warming up of the samples.) The result is shown in Fig. 3. The amorphization behaviour of pure AlAs is very different even from that of $Al_{0.96}Ga_{0.04}As$. Thus, even a small admixture of Ga atoms is crucial. Presumably there is, contrary to GaAs, no energetic barrier for the recombination of vacancies and self-interstitials in AlAs [35]. An admixture of Ga atoms due to implantation-induced intermixing leads to the creation of such a barrier and to a much faster amorphization of the AlAs layers in the superlattice. As can easily be seen, the SL with a period of (1.4 + 1.4) nm behaves like an alloy with $x = 0.5$, whereas the behaviour of that with a period of (10 + 10) nm is already quite peculiar. Thus, it is very probable that the above-mentioned coherent amorphization of the Si and Ge layers in short-period Si/Ge SLs is a consequence of the fact that these SLs behave like SiGe alloys with the same integral Ge content. Further, a layer thickness of 10 nm is already “above threshold”: the AlAs/GaAs SL does not behave anymore like an alloy, there is no coherent amorphization of different layers. Finally, for the AlAs/GaAs SL with a period of (70 + 83) nm a selective damage and amorphization behaviour was clearly observed in the RBS spectra (not shown) [35]. As was shown in Ref. [36], the broadening of an initially 0.27 nm wide AlAs/GaAs interface inside the damage cluster of a single ion amounts to ~2 nm. Hence, our results point to the intermixing in the collision cascades as the reason of the observed coherent SL amorphization.

However, it is noteworthy that the theoretical description of the crystalline-to-amorphous transition upon ion irradiation is still a matter of debate [37].

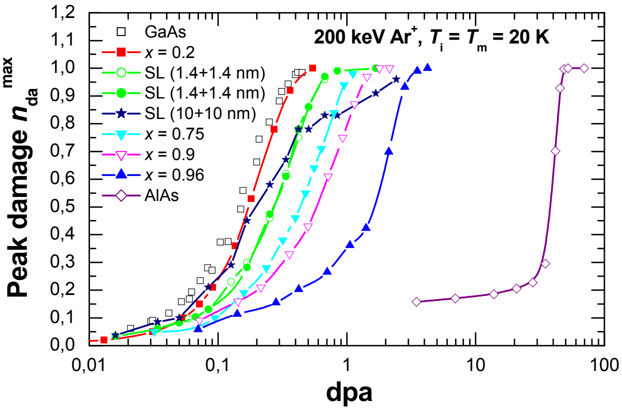

**Figure 3.** Concentration of displaced atoms in the maximum of the damage profile (expressed in displacements per atom, dpa) vs. fluence of 200 keV Ar+ ions implanted into $Al_xGa_{1-x}As$ alloys with various $x$ values and into two GaAs/AlAs superlattices with periods of (1.4 + 1.4) nm and (10 + 10) nm ($T_i = T_m = 20$ K). [34]

## IV. RADIATION TECHNOLOGY

Radiation treatment can be used to improve the performance of QSSS-based devices or to modify their characteristics in a desired manner. New structures can be fabricated due to self-organization upon irradiation.

Ion-induced intermixing is particularly important in the QW laser fabrication (e.g. GRINSCH: graded-index separate confinement heterostructure) [38]. Independently of the amount of intermixing in the collision cascades, the mixing can be strongly enhanced by post-irradiation heat treatment and occurs due to defect-enhanced diffusion [39].

A very interesting and useful phenomenon is the self-organized creation of nanopatterns on the surfaces of targets irradiated by ion beams at low and intermediate energies. So, submicron ripples on various surfaces [40,41] and nanometric dots on GaSb [42] can be produced by ion-beam sputtering. The dots even form a highly ordered array with hexagonal symmetry [42]. Later on, nanodot production was reported in many other materials

Among the most known manifestations of the self-organization upon irradiation process is the formation of nanocrystals (NCs) in ion-implanted semiconductors and oxides. Since there are comprehensive reviews in this area ([43–46]), let us mention only the creation of magnetic NCs embedded in semiconductor matrices. The process opens the way to diverse spintronic applications. Ferromagnetic nanodots are basic elements for fabrication of various devices, for detection of magnetic field and for information recording [47]. As in the other cases described above, the ion implantation offers a versatile tool for nanofabrication. The state of the art as of beginning of 2008 has been reviewed in [48].

An ion track based approach to nano- and microelectronics has been developed in [49].

## V. CONCLUSION

Influence of particle radiation on semiconductor quantum size structures has been reviewed. The QD heterostructures and QD lasers are generically more resistant to radiation damage (“radiation hard”) than their bulk and 2D counterparts, which is caused not only by the localization of the wave function of the confined carriers but also by the expulsion of the mobile defect components to the surface/interface of the nanocrystals. This is very important in atomic energy and space applications. There are many exciting applications of particle irradiation to the QSSS technology, such as intermixing, self-organized formation of surface nanostructures, and ion-beam synthesis of nanocrystals in solid matrices. A promising area is the ion-beam synthesis of magnetic nanocrystals in solid hosts. The dependence of the amorphization kinetics of different layers in a SL on their thickness upon ion implantation in Si/Ge and AlAs/GaAs SLs reveals an intimate relation to intermixing phenomena in solids.

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## REFERENCES

[1] E.G. Stassinopoulos and J.P. Raymond. Proceedings of the IEEE **76** (1988) 1423.

[2] For a review, see e.g. Landolt-Börnstein. Vol. **22** “Semiconductors”, subvol. b “Impurities and Defects in Group IV Elements and III-V Compounds”. Ed. M. Schulz. Springer-Verlag, Berlin e. a.

[3] For the most recent update, see Proc. 25th International Conf. on Defects in Semiconductors (St Petersburg, Russia, 2009), Physica B, in press.

[4] N.A. Sobolev, F.P. Korshunov, R. Sauer, et al. J. Cryst. Growth **167** (1996) 502.

[5] V.I. Gubskaya, P.V. Kuchinskii, and V.M. Lomako. Radiation Effects **55** (1981) 35.

[6] N.M. Santos, N.A. Sobolev, J.P. Leitão, M.C. Carmo, D. Fuster, L. González, Y. González, W. Wesch. Submitted for publication.

[7] C. Weisbuch, J. Nagle. In: Science and Engineering of 1D and 0D Semiconductor Systems, C.M. Sotomayor-Torres, S.P. Beaumont, eds., NATO ASI Series B**124** (Plenum, New York, 1990), p. 319.

[8] N.A. Sobolev, A. Cavaco, M.C. Carmo, et al. Phys. Stat. Solidi (b) **224** (2001) 93.

[9] R. Leon, G.M. Swift, B. Magness, et al. Appl. Phys. Lett. **76** (2000) 2074.

[10] A. Cavaco, N.A. Sobolev, M.C. Carmo, et al. Phys. Stat. Solidi (c) **0** (2003) 1177.

[11] F. Guffarth, R. Heitz, M. Geller, et al. Appl. Phys. Lett. **82** (2003) 1941.

[12] P.J. Wellmann, W. Schoenfeld, J.M. Garcia, and P.M. Petroff. J. Electron. Mater. **27** (1998) 1030.

[13] W.V. Schoenfeldt, C.-H. Chen, P.M. Petroff, and E.L. Hu. Appl. Phys. Lett. **73** (1998) 2935.

[14] J.M. Gérard, O. Cabrol, and B. Sermage. Appl. Phys. Lett. **68** (1996) 3123.

[15] D. Lacombe, A. Pochet, J.-M. Gérard, and O. Cabrol, Appl. Phys. Lett. **70** (1997) 2398.

[16] K.K. Lindner, J. Phillips, O. Qasaimeh, et al. J. Vac. Sci. Technol. B **17** (1999) 1116.

[17] N.A. Sobolev, H. Presting, unpublished.

[18] D. Pons and J.C. Bourgoin. J. Phys. C **18** (1985) 3839.

[19] D. Stievenard, X. Boddaert, and J.C. Bourgoin. Phys. Rev. B **34** (1986) 4048.

[20] D. Stievenard, X. Boddaert, J.C. Bourgoin, and H.J. von Bardeleben. Phys. Rev. B **41** (1990) 5271.

[21] G.M. Dalpian and J.R. Chelikowsky. Phys. Rev. Lett. **96**, 226802 (2006).

[22] Ch. Ribbat, R. Sellin, M. Grundmann, et al. Electronics Letters **37** (2001) 174.

[23] P.G. Piva, R.D. Goldberg, I.V. Mitchell, et al. Appl Phys Lett. **77**, 624 (2000).

[24] J.W. Mares, J. Harben, A.V. Thompson, et al. IEEE Trans. Nucl. Sci. **55** (2008) 763.

[25] N.V. Baidus, V.K. Vasilev, Yu.A. Danilov, et al. In: Design of Radiation-hard Semiconductor Devices for Communication Systems and Precision Measurements (TALAM, Nizhni Novgorod, 2003), p. 59 (in Russian).

[26] N.A. Sobolev, A. Fonseca, J.P. Leitão, et al. Phys. Stat. Sol. (c) **0** (2003) 1267.

[27] V.V. Ursaki, I.M. Tiginyanu, O. Volciuc, et al. Appl. Phys. Lett. **90**, 161908 (2007).

[28] D.J. Eaglesham, J.M. Poate, D.C. Jacobson, et al. Appl. Phys. Lett. **58** (1991) 523.

[29] D.Y.C. Lie, A. Vantomme, F. Eisen, et al. J. Appl. Phys. **74** (1993) 6039.

[30] T.E. Haynes and O.W. Holland. Appl. Phys. Lett. **61** (1992) 61.

[31] B. Breeger, E. Wendler, Ch. Schubert, and W. Wesch. Nucl. Instr. and Methods B **148** (1999) 468.

[32] M. Vos, C. Wu, I. V. Mitchell, et al. Appl. Phys. Lett. **58** (1991) 951.

[33] N.A. Sobolev, K. Gärtner, U. Kaiser, et al. Materials Science Forum **248-249** (1997) 289.

[34] N.A. Sobolev, U. Kaiser, I.I. Khodos, et al. Mat. Res. Soc. Symp. Proc, Warrendale, PA, USA, 1999, Vol. **540**, p. 91.

[35] N.A. Sobolev, B. Breeger, E. Wendler, W. Wesch, I.I. Khodos, R. Hey, H.T. Grahn. To be published.

[36] M. Bode, A Ourmazd, J. Cunningham, and M. Hong. Phys. Rev. Lett. **67** (1991) 843.

[37] H. Bernas. In: Radiation Effects in Solids, ed. by K.E. Sickafus et al. (Springer, Dordrecht, 2007), Chap. 12, p. 353.

[38] For a review of QW intermixing, see, e.g., IEEE J. Selected Topics in Quant. Electron. **4**, No. 4 (1998).

[39] N.A. Sobolev, J. Gerster, G. Mauckner, et al. Nucl. Instr. and Methods B **136-138** (1998) 1057.

[40] M. Navez, D. Chaperot, and C. Sella. Compt. Rend. Acad. Sci. **254** (1962) 240.

[41] W.L. Chan and E. Chason. J. Appl. Phys. **101** (2007) 121301.

[42] S. Facsko, T. Dekorsy, C. Koerdt, et al. Science **285** (1999) 1551.

[43] A. Meldrum, S. Honda, C.W. White, et al. J. Mater. Res. **16** (2001) 2670.

[44] P. Mazzoldi and G. Mattei. Riv. Nuovo Cimento. **28** (2005) 1.

[45] A.L. Stepanov and I.B. Khaibullin. Rev. Adv. Mater. Sci. **9** (2005) 109.

[46] H. Bernas and R. Espiau de Lamaestre. In: Radiation Effects in Solids, Ed. by K.E. Sickafus et al. (Springer, Dordrecht, 2007). Chap. 16, p. 449.

[47] J.I. Martín, J. Nogués, K. Liuc, et al. J. Magn. Magn. Mater. **256** (2003) 449.

[48] N.A. Sobolev. In: Handbook of Self Assembled Semiconductor Nanostructures for Novel Devices in Photonics and Electronics, ed. by M. Henini (Elsevier, Amsterdam et al., 2008), Chap. 13, p. 392.

[49] D. Fink, A.V. Petrov, W.R. Fahrner, et al. Int. J. Nanoscience **4** (2005) 965.