Sergei Chikichev

The major summer event in the Russian semiconductor community was a July workshop 'Silicon-2004' organised and hosted by the Institute of Geochemistry of the Siberian Branch of the Russian Academy of Sciences (IG SB RAS) in Irkutsk (Fig 1). Some 150 participants from all corners of Russia and abroad (Belarus, Ukraine, Kazakhstan, Germany, Hungary, India) gathered in the beautiful Pribaikalskii hotel - at the birth place of the Angara river - to discuss all aspects of science and technology of the element No 14, the emphasis being placed on 'solar' silicon.

Russian solar on Baikal

At first glance, it may seem rather strange, since Russia is known to be enormously rich in fossil fuels, which constitute the lion share of its privatised export. But the obvious fact is that all those excavated substances (oil, gas, coal) are limited in extent and the end of their supply worldwide is already evident even to unaided eye. So much so, that all intelligent people in the world recognise that renewable energy sources are badly needed for humankind survival, even within the current century. Solar energy is one - but the most important, pure and practically inexhaustible - of such resources.

In order to compete with traditional (very dirty, huge amounts of carbon di- and mono-oxide generating) mazut- and coal-feeded electric power sources, the photovoltaic (PV) industry must grow by a factor of 10^3 - 10^4 within the next 50 years. For many countries in the world it could be simply an enforced necessity. If so, a severe shortage problem will be encountered and - fortunately! - is foreseen. Since silicon is the major workhorse for PV (accounting for over 90% solar cells produced worldwide presently) a critical issuehas become the raw material supply,or the so-called 'silicon feedstock problem.'

What silicon shortage?

In a recent survey [1] by experts in the field from USA-based PV Crystalox Solar (major user

Fig 2: (L to R) Profs A I Nepomnyashchikh and Alexander L Aseev agree that Siberia's potential in solving solar-grade silicon feedstock problem is greatly underestimated by local as well as world experts.

Fig 1: Bird's eye view, under the plane wing, of Irkutsk.

and leading producer of single crystal and multicrystalline silicon) Russia has been simply out bracketed from the discussion. Several presentations on Baikal's workshop amply demonstrated that this may well be a shortsighted approach (Fig 2). Regardless of the fact that its IC industry is almost extinguished, Russia still has all the necessary raw material, scientific, technological and industrial potential to become a serious player on the solar-grade silicon feedstock stage.

Moreover, Russia has itself has a multi-GW-scale market for PV panels and plants due simply to its enormous area and much dispersed rural population suffering badly from electric power shortage. For example, the largest island on Baikal - Olkhon - a major tourist attraction, is almost completely lacking electricity. And the Siberian chapter of the Russian silicon semiconductor community has some far-reaching plans to this end, despite almost zero support from an 'oil-stinking' government.

Suffice it to say that CEOs of all silicon plants (metallurgical as well as electronic grade) from all newly independent states that were present, actively participated in the workshop.

Fig 4: Professor Anatoly Dvurenchenskii with high purity m-Si at Shelekov's silicon plant. His paper discussed germanium quantum dot electronic and optical properties and potential for PV devices with widely tuned spectral sensitivity.

Composition	Bural-Sardag quartzite (%)	Charcoal Ash=1.5%	Oil-coke Ash=0.06%	Wood-chips Ash=0.5%	Electrodes Ash=1.0%
Fe_2O_3	0.0005	3.6	10.6	6.9	14.8
Al_2O_3	0.008	0.31	5	3.1	12.5
CaO	0.0005	54	12.5	34.4	3.51
P_2O_5	0.0001	0.23	0.248	0.3	0.0
B	0.0001	0.009	0.15	0.008	0.008
TiO_2	0.0005	0.26	0.18	0.15	1.23
NiO	0.0001	0.02	4.01	0.005	0.19
Cr_2O_3	0.0001	0.006	0.07	0.01	0.15

Source: A I Nepomnyashchikh "Multi-crystalline silicon as a basic PV material" [2] (in Russian).

TABLE 1: Chemical composition of ingredients used for production of up- graded metallurgical Si at Shelekhov's Silicon plant.

Average impurity concentration in solar-grade Si (10-4%)							Electrical properties		
Sample No	Al	Fe	Ca	Mg	Mn	B	Specific resistivity (in Ω• cm)	Carrier concentration (in 10^{17} cm^{-3})	Carrier mobility (in cm^2 $V^{-1}s^{-1}$)
Krs-37-1	N/A	1.0	5.0	2.0	1.0	10	0.1	7	110
Krs-49-2	2.3	3.0	9.0	0.7	0.5	7.0	0.085	7.3	101
Krs-59	0.55		0.4	N/A	0.4	1.0	7.0	0.05	11 120
Krs-69	1.0	3.0	<10	3.0	2.0	7.0	0.07	9	100
Krs-93	N/A	N/A	N/A	N/A	N/A	N/A	50	0.003	360
Krs-99	N/A	N/A	N/A	N/A	N/A	N/A	2	0.14	240
Multi-Si from USA	50	30	<10	15	2	2	1	0.2	240

Source: A I Nepomnyashchikh "Multi-crystalline silicon as a basic PV material" [2] (in Russian).

TABLE 2: Impurity content and electronic properties IG SB RAS-made multi-crystalline solar-grade silicon.

The workshop reveals that Siberia is wonderfully rich in unique (low-boron) (Table1) quartzite (Fig 3) deposits, quite suitable for cost-effective production of multicrystalline large-grain solar silicon by thoughtful recrystallisation of relatively cheap metallurgical-grade silicon (m-Si) produced from these quartzites.

A proprietary 'magic' is that m-Si in itself should be specially cleansed (during moulding and casting. An opening talk delivered by the vice-director of IG SB RAS Professor Alexander Nepomnyashchikh (Fig 2) was about the original patented technology developed at the Institute for production of high-performance (Table 2) multicrystalline Si for PV purposesexactly accordingto an 'all-solid' route, completely avoiding all the unhealthy chlorsilanes.

In general, the range of topics discussed was extremely wide. It went from atomic-scale picturesque in-situ Reflection Electron Microscopy movies of sublimation, with step bunching and debunching, surface superstructure transformations and homo- and hetero-epitaxial processes on silicon surfaces with (111) and (100) orientations by Dr A V Latyshev -ISP SB RAS, Novosibirsk [2] to proposals for multi-kilotonnes production of solar-grade silicon using quite specific ('all-Russian') technologies based on lithium hydride (an H-bomb manufacture by-product, with a huge and dangerous waste feedstock available in Russia) to an environment-friendly plasma-based oxide-decomposing schemes for silicon manufacturin by Dr G-N B Dandaron of Ulan-Ude, of Buriyat Science Center of SB RAS [2]).

Solar efficiency means III-Vs

An interface with III-Vs is simply inevitable when speaking about the highest efficiency PV cells.

Silicon is evidently the best (largest and cheapest) substrate for multi-junction high-efficiency III-Vs solar cells.

Prof. Oleg Pchelyakov from the Institute of Semiconductor Physics (ISP SB RAS, Novosibirsk [2]) reported on the latest developments at his department on integration of Si and Ge with advanced III-Vs heterostructures for PV and TPV cells, including artificial Si/SiGe substrates and band gap engineering with Ge quantum dots in silicon matrix.

A fine discussion of Ge QD electronic and optical properties and their potential applications to photosensitive devices with widely tuned spectral sensitivity was provided by Prof Anatoly V Dvurechenskii (ISP SB RAS [2] (Fig.4). An exciting presentation entitled: "*From silicon micro- and nano- electronics to silicon quantum computing*" was given by Professor A A Orlikovskii from Moscow Physico-Technological Institute (RAS).

Fig 3: High-purity quartzite deposits are measured in 'mountains' in Siberia.

Fig 4: 'Silicon' ladies from Novosibirsk (L to R) Drs Olga Sëmenova and Ludmila Fedina against the background molten silicon flow at Shelekhov's silicon plant.

Russia's 'Dele-Cut' for SOI

Some world- class achievements (inter-linked!) in careful the preparation of fully relaxed thin SiGe/Si substrates by various methods was presented by Dr Alexi VNovikov (Fig 5) from Nizhnii Novgorod and Dr L V Sokolov (ISP SB RAS [2]). His views on the evolution of intrinsic and impurity-induced point defect ensembles in silicon crystals subject to different external influences has been generously shared by patriarch in the field - Professor L S Smirnov (ISP SB RAS).

Dr Luidmila Fedina et al (Fig 4) demonstrated amazing HRTEM pictures of dislocations in Si, accompanied by a deep discussion of their (Russian-discovered and still hotly-debated!) photoluminescence properties.

All readers of the *International Technology Roadmap for Semiconductors* are aware that for the near future of silicon, microelectronics SOI (SGOI) structures are of utmost importance. Patented, 100%-Russian, 'Dele-Cut' technology for SOI mass-production has been vividly explained by Dr. Vladamir P Popov (ISP SB RAS [2] Fig 6).

Kazakhstan's colleagues presented the results and perspectives of their own national and quite ambitious 'Silicon Project' (K. B. Tynyshtykbaev *et al* [2]). By the way, depite Kazakhstan lacking metallurgical silicon, they were able to produce high-purity, semiconductor-grade silane (by a really ingenious trick!) from silicon ferro-alloy (F A Mukashev *et al* [2]). Dr Z J Horvath (Hungary) gave an interesting and up-to-date review of applications of Si (Ge) nanocrystals embedded in high-band-gap dielectrics for single-electron transistors and memory and electroluminescence devices.

Fig 5: (L to R) Drs Slava Shmagin and Alexi Novikov at Hay Bay talk on thin SiGe/Si substrates prepared by various methods.

The social programme of the workshop was a complete success. The landing-ship *Barguzin* ride to Hay Bay and the picnic (with an exclusive hot Russian bath - 'banya' - on the shore) will be remembered by all those involved, as well as excursions to the famous and recently reconstructed Baikal Museum with its huge, newly-built aquariums (where almost all Baikal's endemic inhabitants are displayed in vivo) and to Shelekhov's Silicon plant, one of the largest in Russia. As Professor A Orlikovskii proposed the toast at the workshop banquet: "Siberians have repeatedly proved their unique qualities in rescue operations for the sake of Russia - the Moscow Battle in WW2 is only one example. I would like to raise my glass in the hope that Siberian silicon people do the same for the sake of our whole semiconductor community!"

The semiconductor industry is far from being the major consumer of silicon, but silicon single crystals (and multicrystalline ingots) are an example of industry products of singular significance for our telecoms civilisation, which entered irreversibly into an information, yet severe energy-shortage era. Using silicon (and III-Vs!) PV cells and modules and multi-MWp-scale plants are an obvious choice for sustainable power supplies. Sky-rocketing oil prices will certainly whip up R&D in this field. As a recently popular Soviet child's song puts it: "Let the sun always shine!"

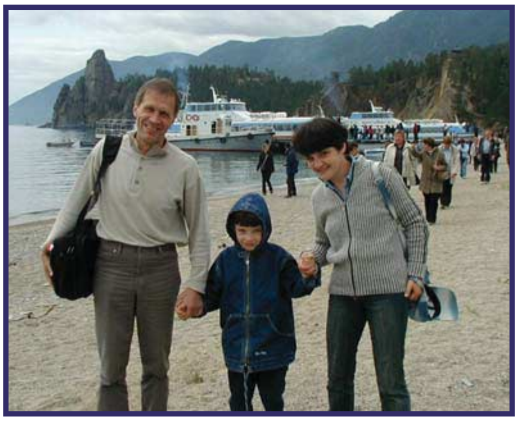

Fig 6: (Left) Dr Vladamir Popov 'Dele-Cut' proponent at Hay Bay.

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References 1. H. Aulich, F.-W. Schulze. *Renewable Energy World*, v.5, No 6 (Nov.-Dec. 2002).
2. Proceedings of '*Silicon-2004*' workshop, CD-Edition, Irkutsk, IG SB RAS, 2004 (most in Russian).