Technology roadmap “The use of nanotechnologies in the manufacturing of LEDs”

Executive Summary

The technology roadmap “The use of nanotechnologies in the manufacturing of Light-Emitting Diodes” (hereafter – roadmap) summarizes the opinion of the expert community about most important technologies, which are used in the production of LEDs as well as other products, based on the LED technology.

The roadmap describes the demand structure for LEDs and points out the prospective markets, to which the production of LED equipment may be oriented. The roadmap evaluates the possibilities of the technologies to provide key consumer properties of LEDs, allowing to figure out the significant competitive advantages for the LED based products.

The general description of LEDs

Light-Emitting Diode, LED - is a semiconductor device emitting incoherent light while letting through current electricity. The modern LED is a multilayer thin-film structure. The layers may be measured on a nanoscale.

Inorganic Light-Emitting Diode (LED) – diode with a structure of only inorganic compounds. It’s a pioneer type of the light diodes, discovered in 1907 and commercially used starting from the mid-sixties.

Competitive advantages:

- high energy efficiency for many applications
- long-term lifetime
- electrical safety due to low power supply
- small sizes
- mechanical resistance
- rapid switching rate
- insensibility to low temperatures
- no harmful components (such as Hg)

Organic Light-Emitting Diode (OLED) – diode with a layer structure consisting of organic compounds. This type was invented in 1950 and became commercially attractive approximately 20 years ago. Significant commercial implementation of OLEDs began 5 years ago.

Competitive advantages:

- possibility of getting emitting panels
- use of polymeric organic materials
- expected cost reduction of the production
- technological ground for manufacturing of flexible light sources and screens
- components for hybrid and organic electronic devices

Today, future of some economics sectors is associated with the solid-state light sources. The combination of compact size, high energy efficiency compared to alternative technology solutions and ability of fast luminance management is the main attractive feature. Due to these features LEDs are applied in lighting (as energy effective sources of light, set for intellectual schemes of light management) and information displays (as independent indicators and display panels of both large and small sizes).

One of the most important social and economic effects of the wide use of LED technology is the potential for radical decrease of lighting energy costs which are varied up to 18-20% of all the costs for electricity according to the different estimations.

The requirements of energy and economic security stimulate the development of LED industry as one of the national priorities for many countries – Canada, USA, EU, Japan and China. Significant attention of some Russian Government rules of proceedings, including Federal Target Program entitled “The development of radio electronic and the electronic components base” is devoted to this subject.

The development of LED technologies, which are capable to displace some other information displaying technologies in future, is rooting deep with perspectives of consumer electronics. The major industry players, such as General Electric, Philips, Osram, are focused on the development of the LEDs appropriate for creating transparent and flexible display panels as well as for hybrid gadgets with organic electrical components.

Two main types of LEDs, organic and inorganic, were examined during technological and market outlook research. These two types differ from each other not only by the technology process but also by consumer properties and area of application.

Inorganic LEDs have been produced and used for more than 50 years. Inorganic LEDs are characterized by high mechanical resistance, small sizes, great energy efficiency and high speed of switching. Traditional applications of inorganic LEDs are: illumination and backlight, information displays, creeping lines and large screens.

Inorganic LEDs are produced in two stages. The first stage consists of fabricating the illuminating chips using molecular beam epitaxy and metal-organics vapor deposition. The second stage goes on to assembling the LED: encapsulating, cooling and joining with optical systems. Both stages demand an exquisite technical culture – it's necessary to use the clean rooms and materials of high purity grade.

The major trend for improving the inorganic LED technology is seen in increasing the screen efficiency and durability with simultaneous cost reduction. The solution of these tasks is found in further development of engineering culture and fundamental research.

The factories that perform assembling of LEDs from LED chips, preproduced by foreign companies are most spread in Russia. Only three companies announced chip production on their own. However, lots of fundamental research has been conducted in the field of inorganic LEDs, comparable, in experts' opinion, to the international level. According to experts, establishing the full-scale production of competitive LED chips in Russia is one of the key challenges for of inorganic LEDs.

Wide commercial use of OLEDs started less than 10 years ago. Today, some product application fields may be considered as prospective only for the next 15 years. OLEDs may be characterized by the following main features: promising low cost of ink-jet printing technology, opportunity of inventing not only luminous and reflecting panels with high image quality and large surface area, but flexible and transparent illumination sources and displays, too. The possibility for using OLEDs in hybrid entirely organic electrical gadgets is also seen.

At present, the wide use of OLEDs is seen only in the displays and flat screen TVs segment which is due to better image quality. Some other areas of research should be noted separately. These are associated with the application of OLEDs for lighting – because of the possible commercial use of large-size luminescent panels.

The production of OLEDs includes both sputtering and solution subsidence technique, and also ink-jet printing technology. These technologies are much less demanding of both the equipment and process which in future will allow to reduce some separate parts' cost.

Major trends of technological improvement of OLEDs include increasing their lifetime, expansion of a panel surface area and cost reduction. These tasks may be solved via fundamental research.

There is only one company specializing in OLEDs production in Russia. The fundamental research of OLED technologies is carried out at the insufficient level. However, it's essential to mention of a significant experience in the related areas of organic chemistry that may be used for accumulating scientific potential in a given area. According to the experts' opinion OLEDs production may be very prospective for Russia in the context of possible integration into the international added-value chains.

There are various complex factors retarding the development of LED industry among which a significant pressure from the foreign suppliers and, at the same time, limited resources which make effective development impossible without a mechanism for interaction between both the representatives of the different commercialization stages and market players. The opportunity of joint exposure and discussion of current problems in a given area, setting up of the milestones and track record, integrating efforts of R&D partners, companies and distributors are the main tasks of such a networking platform.

This roadmap gives an example of a possible communication format and describes the basic trends for the LED industry. The roadmap is developed with the participation of all the types of market players as well as scientific community members, reflecting their opinions. Moreover, the format of the roadmap has a certain amount of flexibility taking into

account additional experts' views. Embodied approach gives an opportunity for mutually beneficial discussion of the listed promising technologies, scientific and development activity milestones and the assessment of attractive market segments by a wide range of experts. Such a discussion is not only desirable but even required for effective application of the roadmap. The best result of the proposed approach is achieved with regular roadmap updates from all key stakeholders.

World LED market

During the last ten years the world LED market has seen a rocketing growth. But it slowed down due to a recent financial crisis. Nevertheless, it is expected that starting from 2010 the market will return to positive. This particular forecast implies three scenarios:

- **Optimistic scenario** assumes that the financial crisis will only drop down the growth rate to a zero point (in value terms). After that together with a world economy renewal the LED market growth rate will be close to 20-25% a year. Popularization (incl. regulative) of LEDs implementation in lighting products; mobile market development (laptops, cell phones, etc.); price decrease together with a LEDs consumer properties improvement will be the main factors of the market growth.
- **Pessimistic scenario** is based on the assumption that the world economy difficulties will be protracted in time. Slow and gradual increase will start not earlier than a second half of 2011. The consumers are enough conservative and loyal to alternative products. The market growth rate in this case is expected to be 5-6% a year.
- **Moderate scenario** assumes that market will resume its growth after a 5% decrease (in value terms) in 2009. Initially (in 2010), it is going to be a compensational rise, 15-20% a year and then the growth rate will be steady at a level of 10-12% a year (in money terms).

The relative dynamics of all scenarios is shown on a diagram below.

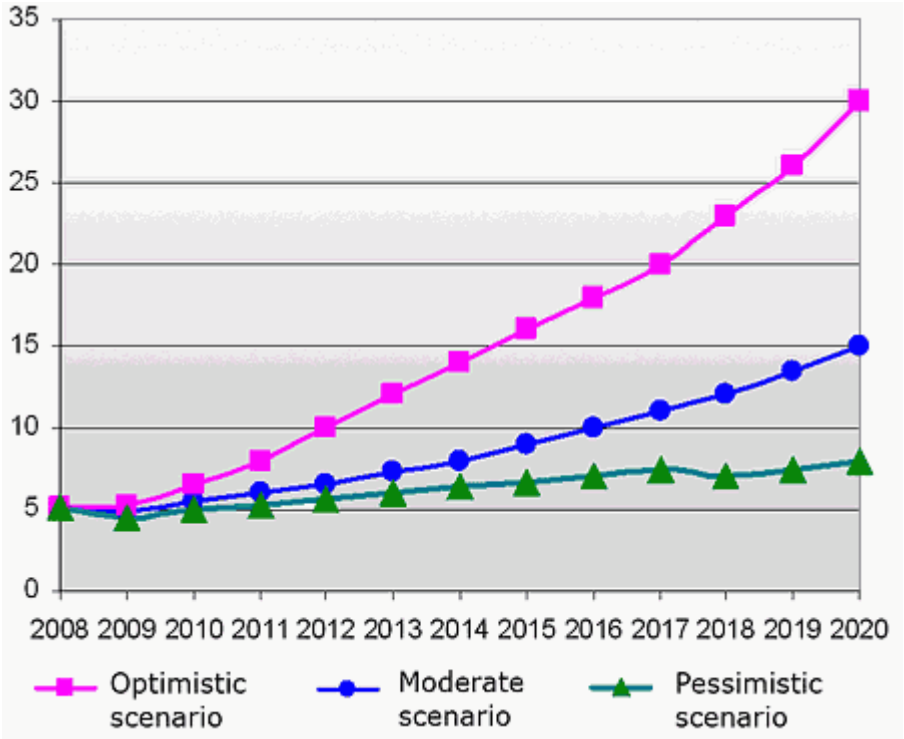

Figure 1. Expected dynamics of the LED world market (USD, billions)

Russian LED market

The Russian market was developing twice as slower as the world market even during the times of rapid growth. The market growth rate in 2001-2003 was about 20-25%, in 2004-2008 it declined to 10-12%. The three possible scenarios are proposed (shown on a diagram):

- **Optimistic scenario** stipulates that the Russian market may account for 5% of the world market due to huge country territory, adverse weather conditions and innovative consumption patterns and also because of the government support and timely solution to the regulative problems.
- **Pessimistic scenario** assumes that because of the consumer passivity, regulatory system imperfection, weak market focus of the producers and other unfavorable factors Russian market will not be able to exceed 1% of the

world one.

- **Moderate scenario** has an inertial pattern assuming that the Russian LED market development will only reach precrisis level in a long term perspective (the market growth rate will remain as twice as slower as the world market).

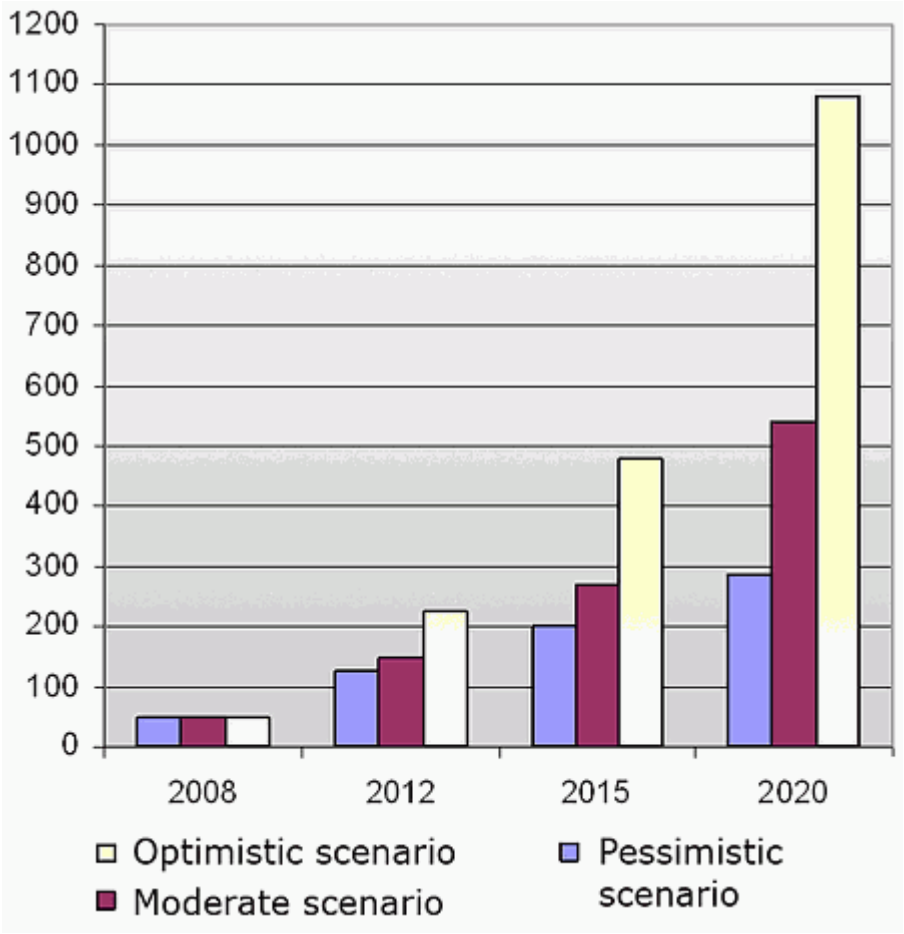

Figure 2. Expected dynamics of Russian LED market volume (USD, millions)

Comparison with alternative technologies

1. Luminescent and micro-light technologies

Filament bulbs		
Traditional Bulbs, halogen bulbs, halogen bulbs with infrared coating, etc.		
Advantages Continuous emission spectrum; low cost; small sizes; lighting fittings simplicity; no toxic components; capability to function either on constant or alternating current; variety of bulbs voltage (0.1 to hundreds volts)	*Disadvantages* Low luminous efficiency; short lifetime; sharp dependence of both luminous efficiency and lifetime on voltage; color temperature lays within only 2300-2900K that yellows the light	*Technology prospects* Novel engineering decisions able to raise the energy efficiency to 40% and filament bulbs lifetime to 100% (IRC- halogen bulb). However, the technology is close to the dead end, no further improvement is expected
Low-pressure discharge bulbs		
Luminescent and compact fluorescent bulbs		

Advantages Light efficiency close to 40-60 lm/W, may be higher for cold cathode bulbs; longer lifetime for serial products – 5 000-10 000 hours; low overhead brightness	*Disadvantages* Contains Hg (Mercury) and requires special disposal; more time needed for lighting up and reaching the full power; sophisticated dimming; electromagnetic emission; side ultraviolet emission; mechanical fragility; large sizes; impossibility of use at low temperatures; light flux pulsation, linear light spectrum	*Technology prospects* An increase of luminous efficiency by 10-15% in the next 10 years, cost decrease. White light quality and dimming capability issues are being resolved. Hg concentration makes the technology unattractive in most cases. Technology endpoint is almost reached
Plasma-based bulbs, high-effective plasma-based bulbs (HEP), other low-pressure bulbs		
Advantages High energy efficiency; high light flux	*Disadvantages* Large sizes; more time needed for attainment of full power; specific emission spectrum	*Technology prospects* An increase of energy efficiency is expected. Limited use of bulbs is possible with an allowance for its emission spectrum
High-pressure and high-intensity discharge bulbs (HID)		
High-pressure and high-intensity discharge bulbs, bulbs with voltage arc		
Advantages The highest energy efficiency, high light flux	*Disadvantages* Low light quality; big sizes, more time needed for attainment of full power; before restarting more time needed for cooling; starting problems at low temperatures; disposal problems; cooling required during continuous work	*Technology prospects* Limited use because of low light quality (narrow spectrum, inappropriate color temperature). Major development trend – light quality improvement
Electroluminescent bulbs with luminophors		
Advantages Energy efficiency close to parameters of compact fluorescent bulbs; ecological safety; dimming ability; momentary start	*Disadvantages* Large sizes, short lifetime	*Technology prospects* Limited distribution and experience in application. Commercial potential is not revealed
Electroluminescent cords		
Advantages Flexibility; low energy consumption	*Disadvantages* Low power; inapplicable for illumination	*Technology prospects* Quite prospective for buildings, cars

		and outdoor advertisement decorating (presently used)
Non-electrical light sources		
Luminophors with a continuous afterglow		
Advantages Energy consumption is not required for illuminating	*Disadvantages* Low brightness, limited illuminating time	*Technology prospects* Applicable for road signs and information displays. A raise of time persistence is expected
Petrol lamps, candles, etc.		
Advantages No need for power supply, technology simplicity, low price	*Disadvantages* Not eco-friendly, inflammable, require maintenance cost (fuel purchase and etc.)	*Technology prospects* Technology development is not expected
LEDs		
Single-unit LEDs and LED matrix		
Advantages High light efficiency; long lifetime; low supply voltage; no toxic components; ability to regulate brightness and emission color; smart control; ability to function at low temperatures (to tenth of K); wide range of color temperatures 2 500 – 10 000 K	*Disadvantages* High price at present; heat control problems; efficiency loss during power and temperature rise	*Technology prospects* Price decrease and light efficiency rise; improvement of both white light quality and integration into infrastructure is expected
OLEDs		
Light-emitting OLED panels		
Advantages High light efficiency in prospect; ability to produce flexible and semitransparent light-emitting panels; expected production cost decrease; low overhead brightness	*Disadvantages* The technology is on the development stage, insufficient lifetime (fast degradation)	*Technology prospects* Essential price decrease, lifetime and energy efficiency increase is expected

2. Information display technologies

Electronic ink (e-ink)		
Advantages Energy efficiency, eyes	*Disadvantages* Limited coloration; limited sizes; low speed	*Technology prospects* Technology is underway. Widening of technology

are less subjected to fatigue	of image changing (for present samples)	use in mobile devices is expected. Colored displays are expected
Electroluminescent panels		
Advantages Ability to produce thin and flexible displays, potentially low price	*Disadvantages* Low contrast	*Technology prospects* Commercial potential is not clear
LCDs		
Advantages Proven production technology; contrast control (during LED back light); high dynamic range	*Disadvantages* Low efficiency; low image quality at sunlight	*Technology prospects* Expected to be replaced with LED back lighting, energy efficiency increase
Plasma panels		
Advantages Better color rendering (comparing to LCD – CFFL); high brightness, applicable for outdoor use	*Disadvantages* Large sizes; oversize pixel; high price; screen burn-out; degradation of luminophors; electromagnetic emission; high energy consumption	*Technology prospects* According to information received no essential technology parameters improvement in a short-term outlook is expected. General application – outdoor information displays
OLED-displays		
Advantages High color rendering; potentially high energy efficiency; potentially low price; low operational voltage	*Disadvantages* Short lifetime; limitations to a screen size; presently high price; presently unbalanced colors degradation	*Technology prospects* Possible popularization in case of price decrease and OLED displays lifetime prolongation in a middle-term outlook (7-8 years). Essential progress of performance capabilities is looking up
LED displays of matrix type		
Advantages Large size imaging; long lifetime, energy efficiency; high brightness	*Disadvantages* No particular disadvantages in its class. Low resolution	*Technology prospects* Massive use of LED displays for signal and advertisement applications
Silhouetting systems		
Advantages Ability to get large size images	*Disadvantages* Low brightness; limited lifetime; low contrast, sizes	*Technology prospects* Downsizing; popularization of LED technology in the capacity of light sources (for mobile applications)
Laser projectors		

Advantages	*Disadvantages*	*Technology prospects*
High color rendering quality; high contrast	High price; image graininess; emission coherence (unsafe, restriction to power capacity); low resolution; limited use	Cost decrease; development of powerful continuous emission sources in a green light zone

LED market segments

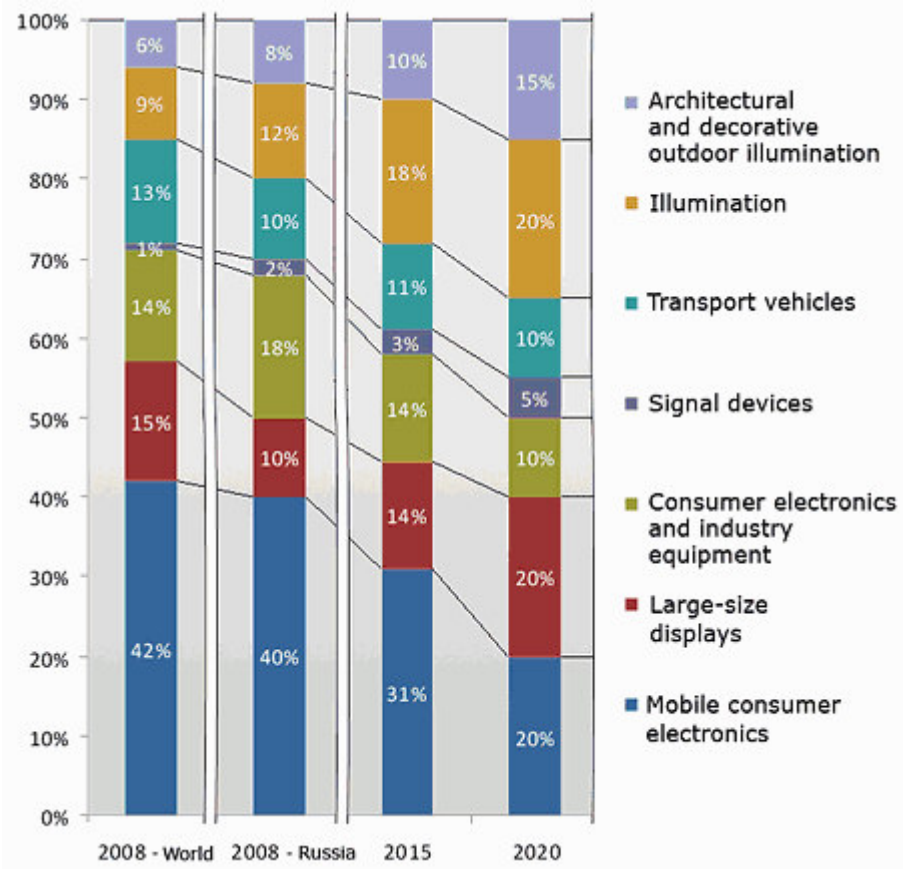

Figure 3. Present and forecasted structure of the LED market (%)

According to the forecast described various LED market segments will be developing differently (refer to the picture).

In a long-term outlook the most high growth rate is seen in the common lighting segment and large-size display segment.

The essential decrease of a market share of the LEDs for mobile devices is expected. The signal devices segment has only 2% of a total LED market and is considered as niche segment.

The market share of LEDs for consumer electronics, including LCDs, will not be changing in the long-term prospects due to 20% increase of such devices' market share. The LEDs are expected to enter the illumination systems' market and, as a result, 17-35% growth of this segment annually.

The prospects of the LED technology in different application segments are given above.

1. Mobile consumer electronics

LEDs	**OLEDs**
Application	
Colored status indicators; LED-flashes; backlight for photo and video equipment, LCDs	Displays
Alternative technologies	

No direct competitors in an indication segment. The share of single indicators is decreasing because of the growth of the integrated indication panels' share. Competition form xenon flashes. Competition form alternative display technologies	LCDs, e-paper, electrical luminescence display (incl. flexible)
Prospects for the LED technology	
Absolute dominance in the LEDs segment for indication. The cheapest small-size LEDs will be claimed. A trend to the growth of the demand for powerful LEDs (for LEDs with power consumption >1W – 20% increase annually). The reduction of a number of single indicators and replacement of them by novel display technologies	In the short and middle term dominance of OLED screens for mobile devices is expected. In the far future – display technology for hybrid devices (using organic components)
Prospects for Russian LED producers	
No domestic production of mobile devices and competition from Asian countries almost exclude a chance to enter this segment. Individual niche applications are possible. For satisfaction of the needs for powerful LEDs new production facilities are required, in this case a possibility to enter the market is pointed out by the experts	There is a chance for successful integration into international value chains. Active involvement in international research activity and consolidation of scientific and industry work are needed
Reasonable measures of state support	
Product demand stimulation, support for the niche products including production placement in Russia, generation of the government order	Support for purchasing of up-to-date research and production equipment, which will allow to combine efforts of both research institutes and industry

2. Large-size displays

LEDs	**OLEDs**
Application	
Backlight for LCDs, large-size LED screens	Displays
Alternative technologies	
Displays using halogen bulbs, other methods of the LCDs backlighting, projection technologies, plasma panels, OLED displays	LCDs, plasma panels, laser and projection technologies
Prospects for LED technology	
LED screens occupy the niche of the large-size video screens. LED backlight for LCDs is becoming more popular stimulating the demand for the bright LEDs	In the middle and long term outlook the development of OLED technology for TV and computer screens is expected
Prospects for Russian LED producers	

Successful assembling of LED screens upon client's requests is possible. This segment demands for white and colored LEDs, including also produced domestically. There is a problem with scale operations and LED price	There is a chance for successful integration into international value chains. Active involvement in international research activity and consolidation of scientific and industry work are needed
Reasonable measures of public support	
Coordination of domestic LED producers' efforts to ensure required specifications of the final devises. Generation of the government order in niche segments (incl. special equipment)	Stable financing during a long time and support for R&D are needed. The researches are to be concentrated in major domestic research centers

3. Consumer electronics and industry equipment

LEDs	**OLEDs**
Application	
Single indicators – colored and monochrome; indicating screens; applications in telecom systems and electronics (optical communication links, fiber transmitting links for digital TV signal, etc.); gauges; LCDs backlighting; other applications (UV indoor and water disinfection, banknote verification devices, plant growth stimulants, etc.)	Displays
Alternative technologies	
In indication segment - displaying technologies. In telecom, electronics and gauges segment – laser technologies. Various competitors in niche applications	Other displaying technologies
Prospects for LED technology	
A cutback in the number of single indicators. Absolute dominance in separate niches	Dominance of OLED-displays for mobile devices
Prospects for Russian LED producers	
Domestic technologies with required specifications and niche application oriented are prospective (gauges, special equipment, medical equipment, etc.)	Entering this segment with simultaneous development of screens for mobile devices is possible
Reasonable measures of public support	
The support of niche applications is prospective. Generation of the government order for the individual products (incl. UV disinfection means)	The support of niche applications is prospective

4. Signal devices

LEDs	**OLEDs**
Application	
Traffic lights, semaphore signals; road information screens; emergency traffic lane markings and signs; control systems, movement sensors, smoke sensors	Light-emitting panels in specified shape

separately and in security systems	
Alternative technologies	
Halogen and luminescent bulbs, electroluminescent bulbs and wires, neon bulbs	Halogen and luminescent bulbs, electroluminescent bulbs and wires, neon bulbs
Prospects for LED technology	
Very promising segment. Lifetime, high energy efficiency, emission spectrum control, rapid switching make the inorganic LEDs a dominant technology in the segment in both short and long term	Presently the application is limited because of an insufficient lifetime and environmental resistant
Prospects for Russian LED producers	
Russian producers have advantage due to proximity to the market. The projects are successful in case of interaction with big enterprises (guarantee and post guarantee services). Russian specific – special requirements for traffic lights LED spectrum (colors cyan, deep red), climatic conditions (LED must not change the color between -60 and +80˚C)	Presently the segment is unattractive
Reasonable measures of public support	
The development of metrological assurance system (state standards, construction norms and specifications, acceptance rules for LED hardware, comparison parameters and regulatory standards) and standardization of the LED systems is required	In the short term the support seems to be unreasonable

5. Transport vehicles

LEDs	**OLEDs**
Application	
Parking lights, blinkers, stop lights with colored LEDs; head lights; car interior lightning; indicating panels; inbuilt electric systems; décor; other applications	Car interior lightning, head-up windshield display
Alternative technologies	
Filament bulbs (halogen bulbs), luminescent and compact luminescent bulbs, electroluminescent bulbs	Filament bulbs (halogen bulbs), luminescent and compact luminescent bulbs, electroluminescent bulbs. Electroluminescent displays
Prospects for LED technology	
LEDs are actively replacing alternative technologies in most applications	The research for transparent displays integrated into a car windshield is being carried out. Massive application of these technologies is expected in the future
Prospects for Russian LED producers	

Potentially high interest from domestic carmakers. Spreading of LEDs on railway transport: power system adaptation, constructive features, selection of spectral component. The requirements development for newly worked out vehicles should be stipulated by existing LED technologies	Promising segment for investing in R&D activity. Close interaction with major carmakers during a long term is required
Reasonable measures of public support	
Stimulating of carmakers to use domestically produced LEDs. The modification of the requirements for transport illuminating equipment. Stimulating of major enterprisers to a conversion to a LED technology base. Support for contracts with carmakers and production localization	Support for purchasing of up-to-date equipment, co-financing

6. Architectural and decorative outdoor illumination

LEDs	**OLEDs**
Application	
Display media; architectural, decorative and landscape illumination	Light emitting panels, including flexible, semitransparent
Alternative technologies	
Filament bulbs, luminescent bulbs, electroluminescent bulbs and wires, high-pressure discharge bulbs	Electroluminescent displays, Electroluminescent wires
Prospects for LED technology	
Resistance, lifetime, controllable spectrum, directivity, small sizes, rapid switching, energy efficiency, smart control make the LEDs most suitable in decorative applications. Using of smart control systems provide more possibilities for decorative illumination as well as for the media displaying	OLEDs are most prospective in terms of indoor installation. In the short term commercial use is not expected
Prospects for Russian LED producers	
Strong competition form South-East Asia countries in LEDs production complicates entering the market. There are prospects for producing of lamps and smart light systems upon particular customer's order	Specific kinds of products may be put on the market
Reasonable measures of public support	
There is a possibility for generation of state procurement of domestically produced decorative illumination equipment, for instance, urban buildings illumination and for important events decorating (Olympic Games 2014 and others)	The support for products ready for the market is reasonable

7. Lighting

LEDs	OLEDs
Application	
LED lamps	Light-emitting panels
Alternative technologies	
Filament bulbs, luminescent bulbs and compact luminescent bulbs, different bulb types	Filament bulbs, luminescent bulbs and compact luminescent bulbs, different bulb types
Prospects for LED technology	
Distribution of LED lamps supported by different countries' government programs	New types of light sources are to appear in the future, such as light-emitting panels (at the beginning compound panels, then solid large-size panels). Novel tendency to overall brightness decreasing
Prospects for Russian LED producers	
Entering this segment is complicated by aggressive policy of foreign competitors. The manufacturing of LEDs is probable in association with foreign producers (also because of patent resistance). Russian producers may be quit successful due to an opportunity for adaptation of the products to the Russian regulatory system	Promising area for R&D investments
Reasonable measures of public support	
Balanced measuring system which includes R&D and production placement support, generation of the government procurement, regulatory documents development, personnel training, forming of a corporate culture is required	Support for R&D, placement of prototype and mass production. Assistance in purchasing of state-of-the-art equipment

Description of roadmap's structure

The roadmap's visual structure consists of three sets: "Colored LEDs", "White LEDs" and "OLEDs". Each set includes five vertical layers which describe the interconnections between major technologies, which define the subject area development, specifications of present and prospective LEDs and the market segments for end-products defining the demand for the LEDs.

Each vertical layer contains the following elements:

1. Technological tasks, defining the improvement of LED technology and its connection with LEDs specifications.
2. LEDs specifications and its connections with prospective markets.
3. Strengths and weaknesses of a corresponding LED type in major purpose segments
4. Alternative products and its competitiveness, main competitive advantages.
5. The forecasts for capacity and growth rate of the main LED market segments.

In a visual structure of the roadmap mentioned elements are marked with numbers.