Increasing light extraction efficiency of GaN LED chip

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ABSTRACT: A light emitting diode (LED) is a semiconductor device, which emits light by electrons moving from a point of high energy level to a point of low energy level when an electric power is applied to it. LED is used in widespread application area from cell phone, automobile lamp, and so on. Increasing efficiency is one of biggest issues on LED. There are several causes to decrease light efficiency of LED. One of the most serious source of light loss lies on low extraction efficiency. Root cause analysis revealed that total internal reflection between GaN / sapphire interface is the main source of low efficiency (harmful effect). By formulating technical contradictions around this issue, we could suggest more than 30 fresh ideas, among which 3 ideas were selected for feasibility test and prior art search. All of 3 ideas have increased light extraction efficiencies 40% up. 2 of the ideas were filed up as 2 patents, which were integrated into commercialized LED chip successfully in October, 2006. Many other ideas that were not accepted at that time have been seed for further research and development milestone of the LED project team.

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Introduction

What is GaN LED?

A light emitting diode (LED)[1] is an illuminating semiconductor diode device. In diode system, current flows easily from the p-side (anode) to the n-side (cathode) but not in the reverse direction. Charge-carriers — electrons and holes — flow and meet together in p-n junction. When an electron meets a hole in the p-n junction, it falls down to a lower energy level, and releases energy in the form of light. The wavelength of the emitting light (color) depends on the band gap energy of the materials forming the *p-n junction*. Direct band gap of LED composing material determines wavelengths of the emitting from near-infrared light to vis./near-ultraviolet light.

Since middle of 1990s, GaN has pulled great interest because of its potential for optoelectronic application, for example light emitting diode (LED) and laser diode(LD)[2]., LCD backlight etc.

Figure 1 shows typical structure of LED system composed of GaN, which comprises light emitting p-n junction (usually called as active layer), n-layer, p-layer, n-electrode, p-electrode, sapphire substrate. Whoever has interests in LED can refer other sources[3] [4]. Nowadays LED is used in many application; cell phone, automobile lamp, backlight for LCD, and so on.

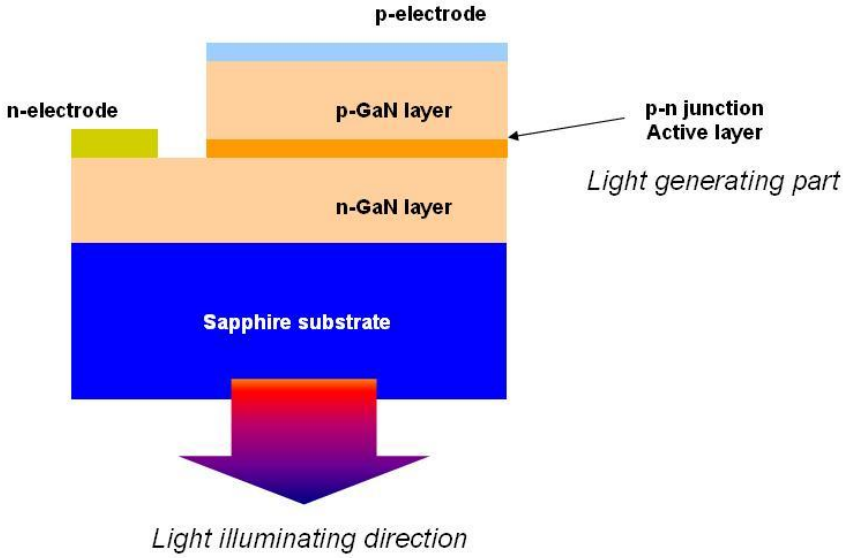


Figure 1 Conventional GaN light emitting diode

What is problem of LED?

Light generating efficiency of LED chip depends on three different efficiencies designated in formula (1).

$$\eta_{WPE} = \eta_i \times \eta_{ex} \times \eta_{el} \quad (1)$$

Where η_{WPE}*: wall plug efficiency of chip*

η_i*: internal quantum efficiency;*

η_{ex}*: extraction efficiency*

η_{el}*: electrical efficiency*

Internal efficiency is light generation efficiency that relies on semi-conducting material, dopant material, nano structure of material (e.g. defects) and so on. Internal efficiency at that time was around 70%, which merely met the eye-level of customers. Electrical efficiency has close relationship with p-contact and n-contact. Electrical efficiency was developing the other member of the team at that time also. The most serious problem laid on extraction efficiency. It was just around 30%.

Leader of the LED team wanted to focus on light extraction as first priority not only because it is most serious one but also because the others are dealt with other members of the team.

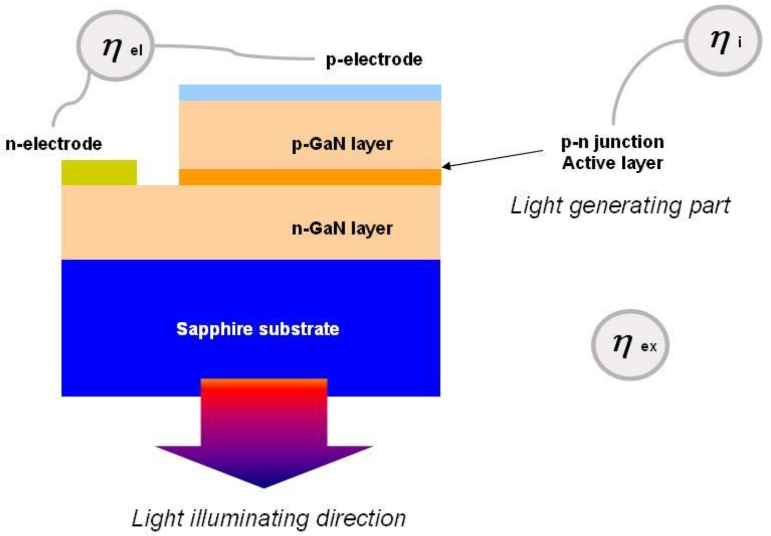


Figure 2 Relationship between efficiency and elements of device

Why problem appears?

Many authors have studied on LED light extraction efficiency issue.[5].[6] [7] [8] Summarizing scientific research results, the authors tried organizing cause-effect map. In the beginning of identifying harmful mechanism, domain experts of LED suggested lots of probable reasons why LED had so poor extraction efficiency from brainstorming with LED experts and TRIZ specialist. TRIZ specialist applied problem formulation technique[9] to construct harmful mechanism in figure 3.

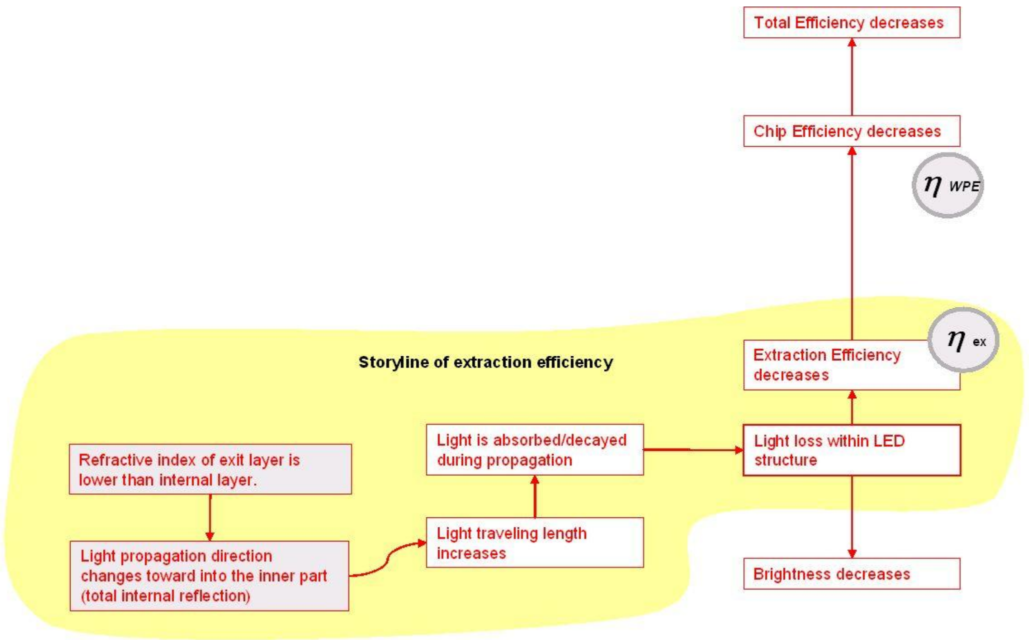


Figure 3 Mechanism of harmful effects (low extraction efficiency of LED chip)

Causality diagram could be constructed by the help of TRIZ SW, for example, Goldfire Innovator™, or Innovation Work Bench® , and many other TRIZ SW. Above causality diagram made domain experts as well as TRIZ specialist identify what is 'real problem'. Summarizing situation in causality diagram, we could understand harmful effect chain from "sapphire is used as substrate of n-GaN layer" → "refractive index of outer layer (sapphire substrate, 1.7, it's nature of sapphire) is lower than that of inner layer (n-GaN, 2.5, it's also nature of GaN)" → "Light propagation direction changes toward into the inner part (total internal reflection)". After identifying critical thread of root causes, it was necessary to understand physical effects, 'total internal reflection', which had main role in harmful effect chain.

To understand why and where we had problem, it was necessary to understand the nature of 'total internal reflection' phenomena more deeply. When light is coming upon from a medium with high refractive index to a medium with lower refractive index, light bends towards interface direction (i.e. away from the normal direction). In this case, exit angle from the normal direction is always bigger than incident angle of the light. As incident angle becomes larger, the exit angle approaches 90°. For some angle greater than critical incident angle θc, the light can't go out from the 1st media. Literally the light is kept in the first media. There is a risk of such total internal reflection where two types of media meets, which have different refractive indices. In LED, the incident light with perpendicular pathway from the substrate/LED interfacial layer

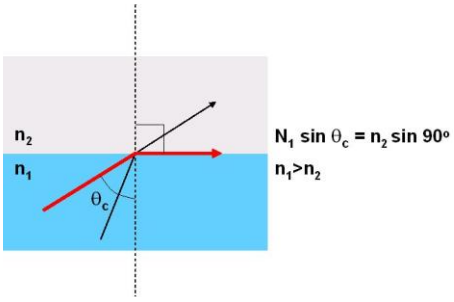


Figure 4 Total Internal reflection

Where problem appears most seriously?

Total internal reflection explains well enough why as-was LED had low extraction efficiency (~30%). It was necessary to create a system to eliminate the harmful effect of total internal reflection mechanism. To design the system, we investigated the resources more deeply, especially operating zone in the LED to identify what places had most serious problem. By drawing refractive index vs. device location showed where we might have most serious total internal reflection. Figure 5 shows specific location clearly; table 1 shows the difference in numerically..

As refractive index difference increases, total internal reflection problem becomes worse. The biggest difference existed between sapphire substrate between n-GaN layer. We wanted to focus on this interface.

Some of TRIZ experts might consider operating zone study should be done very late stage of problem solving, but many contemporary TRIZ experts agree that operation zone study should be started from very early phase of problem solving.

Table 1 Resource analysis for the location of serious total internal reflection

Inner part	N_in (inner part)	Outer part	N_out (outer part)	Δn (in-out)	Severity of total internal reflection
InGaN Quantum well	3.00	N-GaN	2.54	0.46	Medium
N-GaN & buffer layer	2.54	Substrate (sapphire)	1.46	1.12	High
substrate	1.78	epoxy	1.50	0.28	Low
epoxy	1.50	air	1.00	0.50	medium

After analyzing the harmful relationship between sapphire substrate and GaN substrate, TRIZ experts asked domain experts a very stupid question why sapphire existed there with such harmful effect. By asking such simple and stupid question, we could collect meaningful information more and more. Domain experts answered the stupid question as following: because without sapphire substrate, GaN itself can't be formed (This information is common sense for the domain experts that use sapphire as substrate for GaN crystal epitaxial growth). GaN crystal can grow on only crystal substrate with similar crystal structure. Maybe we can use GaN itself as a substrate with same refractive index, but such substrate is much more expensive than sapphire substrate.

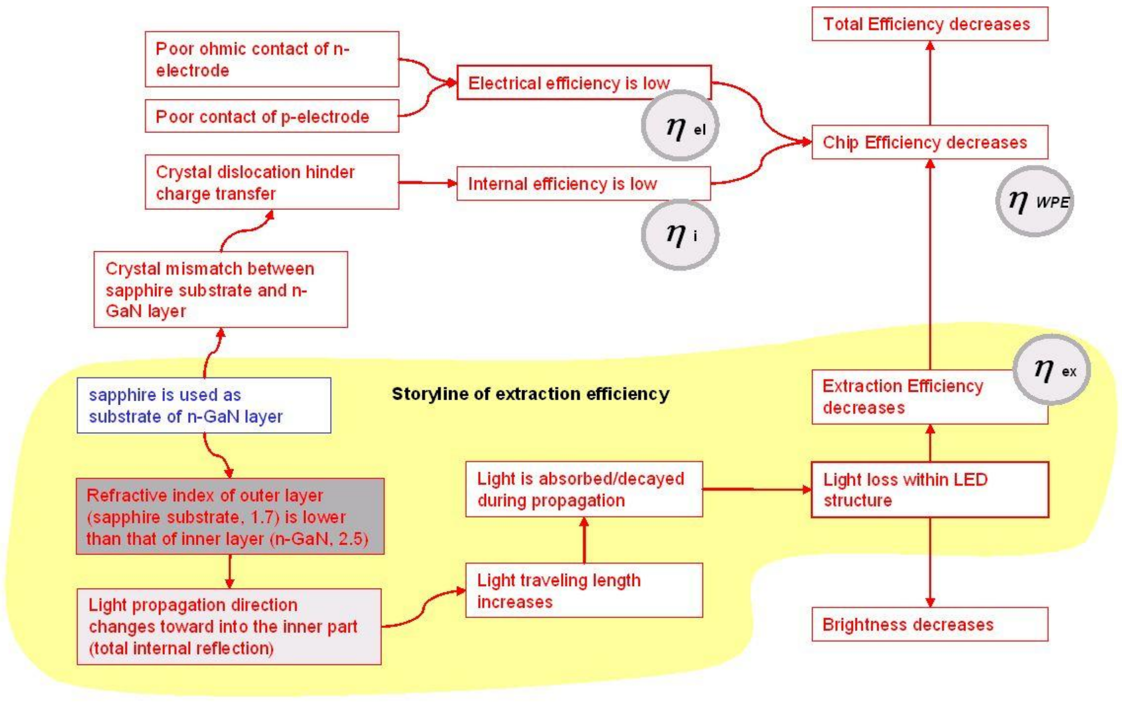


Figure 5 Advanced causality diagram of light extraction problem in GaN LED

TRIZ specialist decided updating causality diagram of light extraction efficiency problem because our old version diagram had no information about the function of sapphire substrate at all. We analyzed the relationship between several events and inserted links between such events as well as collecting supplementary information from several sources.

Yellow background area was our focusing region about extraction efficiency. TRIZ specialist added supplemented stories about **manufacturing condition, internal efficiency** and electrical efficiency. It was not because just flapping our broad knowledge to domain experts but because supplemented information had meaningful links with one of root causes for extraction efficiency. Figure 6 shows the more realistic problem model of light extraction efficiency than the earlier version designated in figure 3. When we got this information from the domain experts, we could understand we are touching the core of the problem. There existed inherent contradiction relationship.

As described in several figures, to extract and understand the problem of the system, it is necessary for TRIZ specialist to have minimal scientific knowledge base as structured form. If TRIZ specialists have no domain knowledge of the system and context of the system, TRIZ specialist t can't guide domain expert to externalize core problem of the system in right ways not because TRIZ is bad but because TRIZ itself can't understand the problem structure.

Transition actions to solve identified root causes

After we made a consensus on the root cause of the system, we could suggest a primary solution to eliminate of the problem. The authors call such primary solution as transition action[10]. It was worth survey known solution for this approach to find out our own intellectual properties not because just copying prior patent but because aligning problem solving direction.

Most interesting feature of known solution is a method of changing interface geometry to change critical angle of total internal reflection. The authors calls such known solution as one of transition action to solve identified root causes to understand and known really to where we should go, i.e. to set up problem solving strategy.

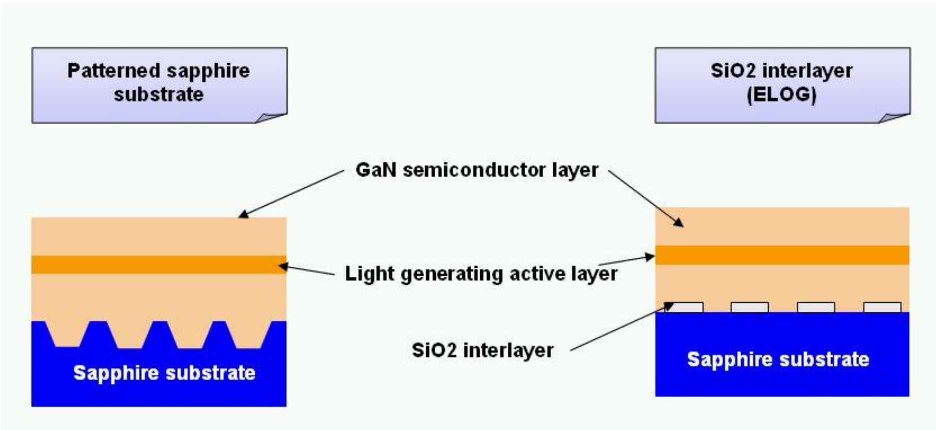


Figure 6 conventional approaches to solve low extraction efficiency Problem model of GaN LED

ELOG (**e**pitaxial **l**ateral **o**ver**g**rowth, right concept of figure 6) [11, 12] technique and PSS (**p**atterned **s**apphire **s**ubstrate, left concept of figure 6)[13] technique was useful technique to reduce total internal reflection between sapphire substrate and GaN. The original purpose of these two techniques was to reduce dislocation density during crystal epitaxial growth. The primary effect of these two techniques is increasing internal quantum efficiency by reducing defects of the crystal. Enhancement of light extraction efficiency is secondary effect of the suggested technologies.

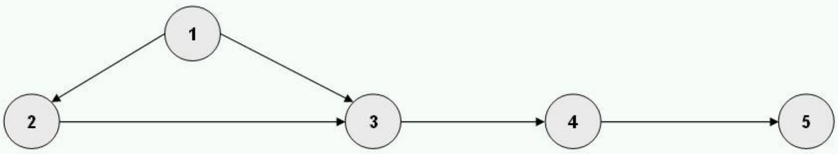
But these techniques had inherent problems. ELOG technique needs introducing additional SiO2 mask layer on the sapphire substrate, which enhances manufacturing complexity. PSS technique doesn't need such mask. Mitsubishi Cable[14] and Toyoda Gosei[15], Nichia[16], Mitsubishi[17] have reported that patterned substrate enhances light extraction efficiency, which means the major competitors claim their light strongly. Conventional PSS process has a drawback of manufacturing efficiency. When growing the semiconductor crystal layer on the conventional patterned sapphire substrate, planarization process should be done after facet growth on the pattern. Facet grows on the top and bottom part of the pattern; crystal re-growth to planar surface, thick layer is necessary. Process to make even surface is called as planarization. Another disadvantage of conventional PSS technique is void formation on the interface of sapphire substrate and GaN. Lateral growth speed is faster than vertical growth speed in GaN semiconductor epitaxial growth. Rapid lateral growth on the conventional groove pattern leads void formation.

Formulating problem model

To formulate problem model, it is necessary to summarize collected information into one. In the beginning of the project, the authors started from [undesirable feature] of the LED system. In problem formulating table[18] designated in table 2, there are several description about the entire story about problem, cause of the problem, 'known' way to resolve known problem, and the problem of such 'known' way (in other words, why we can't use 'known' ways).

Point (1) is usual location where we start describing our situation. Sometimes, description starts from point (2) or (3), but the only important thing is that point (1), (2), (3) should be described fully notwithstanding where description starts. Usually, point [1] is most easily identifiable part in system/problem complex. The authors defines it 'passive knowledge' that undesirable function (point (1)), the reason to eliminate undesirable function (point (2)), the cause of undesirable function (point (3)). Point 4 is starting point of so called active analysis. The authors started to survey 'transition action' to make up over the identified undesirable feature of its origin. The authors analyzed drawbacks of such transition actions and/or why we could use known transition action to eliminate undesirable function in detail denoted in point (5). Table 2 summarizes the logic of TRIZ-like problem formulation from real situation. Table 2 provides a template for problem model formulation also.

Table 2 Problem formulating table: substrate modification



no	The reason to eliminate undesirable feature	Undesirable feature	Origin of undesirable feature	Transition action to eliminated undesirable feature and/or its origin	Child problem of known method or the reason why transition action can't be used
1	Efficiency is low	Extraction efficiency is low	Total internal reflection (phenomenon) between GaN and sapphire substrate (operating zone)	ELOG technique	1.Additional mask is necessary 2.Competitor's strong IP
2				PSS technique	1.Mfg process is slow 2.Void formation on the interface 3.Competitor's strong IP
3					

Technical contradiction could be defined at any hierarchy in system/problem complex denoted in root cause analysis diagram. For the purpose of product design upgrade, competitor's solution for the same problem is a most pragmatic starting point of contradiction resolving journey. We can set competitor's solution as one of transition action for our problem.

We defined our pragmatic contradiction as following.

- ☐ TC1-0: If SiO2 mask is introduced on the sapphire substrate(ELOG technique), total internal reflection is reduced(good), but additional mask generates manufacturing complexity(bad)
- ☐ TC1-1.If SiO2 mask is absent (conventional even structure), manufacturing complexity is minimized (good), but total internal reflection exists(bad).

- ■ TC2-0: If groove pattern is introduced on the sapphire substrate(PSS technique), total internal reflection is reduced(good), but manufacturing process is slow(bad1) and void appears on the interface(bad2)
- □ TC2-1. If groove pattern is absent (conventional even structure), manufacturing complexity is minimized (good), but total internal reflection exists (bad).

According to the domain experts, introducing mask during manufacturing process is very complex, which increases cost of the device. An attempt to direction no.1 is more difficult to solve than direction 2. The authors decided to follow the second direction, i.e. groove introduction. We referred to contradiction matrix and picked up some meaningful inventive principles as following. We chose TC2-0 as main direction of solving, because efficiency enhancing met the requirement of customers.

- ✓ Contradiction using natural language: introduction groove to reduce total internal reflection (good) ←→ manufacturing process time(bad), unwanted void on the interface (bad)
- ✓ Contradiction using 39 parameters: shape ←→ object generated harmful factors, shape ←→ object affected harmful factors

Worsening feature / Improving feature	Object generated harmful factors	Object affected harmful factors
shape	<u>35. Parameter change</u> 01. Segmentation	22. Blessing in disguise 01. Segmentation 02. Separation <u>35. Parameter change</u>

Among recommended principles, no.35 parameter changes seemed most promising direction for further ideation. Controllable parameters in our system could be listed as following. This description comes from simple resource analysis of the system.

- Parameter of incident **light** itself
  - Angle toward the interface
  - **<u>Propagation trajectory</u>**
  - Wavelength
  - Wavelength distribution
  - Polarization, etc.
- Parameter of **media**
  - Refractive index
  - **<u>Shape</u>**

We thought which parameters of the 'shape' of the groove could be changed. Pitch, width, height, shape, refractive index difference, distribution of pitch, width, height, shape and refractive index difference and so on. We picked up 'shape' as one of most changeable parameter of groove. Other researchers (ref) claimed on stripe, rectangular patterns with facet growth on it. **Inventive principle no.14 Curvature**[19] guided one more time to recognize pattern would be promising.

According to spheroidality principles, we could use curvilinear ones instead of rectilinear shapes;

Once deciding to change the shape of the groove to curve shape, we estimated benefits of such variation. GaN semiconductor crystal grows specific direction of crystal structure. Crystal growth on such curved shape is restricted in GaN epitaxial growth. We tried simulating the effectiveness of curved shape on total internal reflection by ray tracing (code V optical simulator, the results is not shown in this article). According to the positive results proven by ray tracing simulator, structure designs were selected for manufacturing process design.

The only problem is a method to develop curved pattern on the substrate. But it was not so hard work to generate curved shape of the groove on sapphire substrate. Using lithography technique[20] domain experts could create curve shape of sapphire substrate. Upon curve patterned sapphire substrate, GaN crystal growth proceeded more rapidly than that of conventional groove pattern.

[Figure 8] summarizes different mechanism of GaN[21] epitaxial crystal growth on two different patterns. Facet formation to grow conventional patterned substrate increase process time of crystal growth, which worsens productivity. But, circular shape of sapphire pattern never grows crystal on it, which accelerates crystal growth more rapidly. Different crystal growth mechanism enabled the domain experts filed their idea as new patent that is different from prior art.

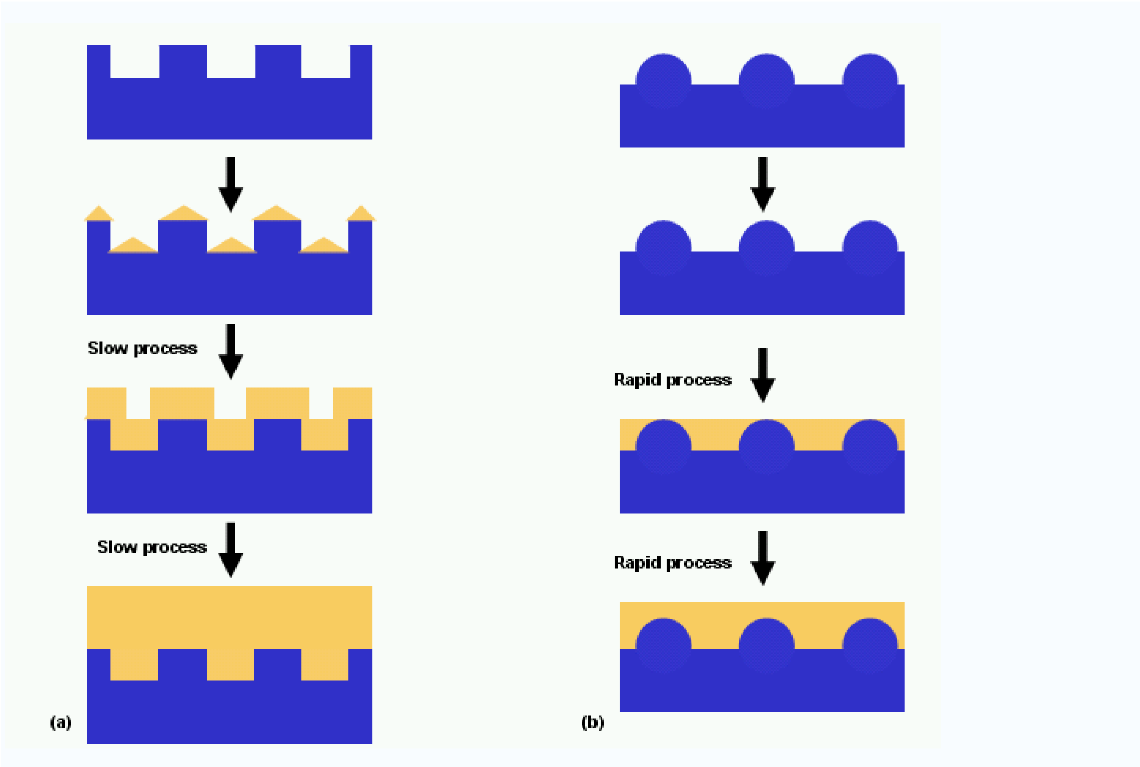


Figure 7 Manufacturing process of conventional PSS(a) and curve PSS (b)

Curved pattern showed excellent light extraction efficiency with minimal irritation in manufacturing process without avoiding known technologies in patents. Curve shape sapphire substrate is one of key technology introduced in LED lamp produced by Samsung Electromechanics, Inc.[22]

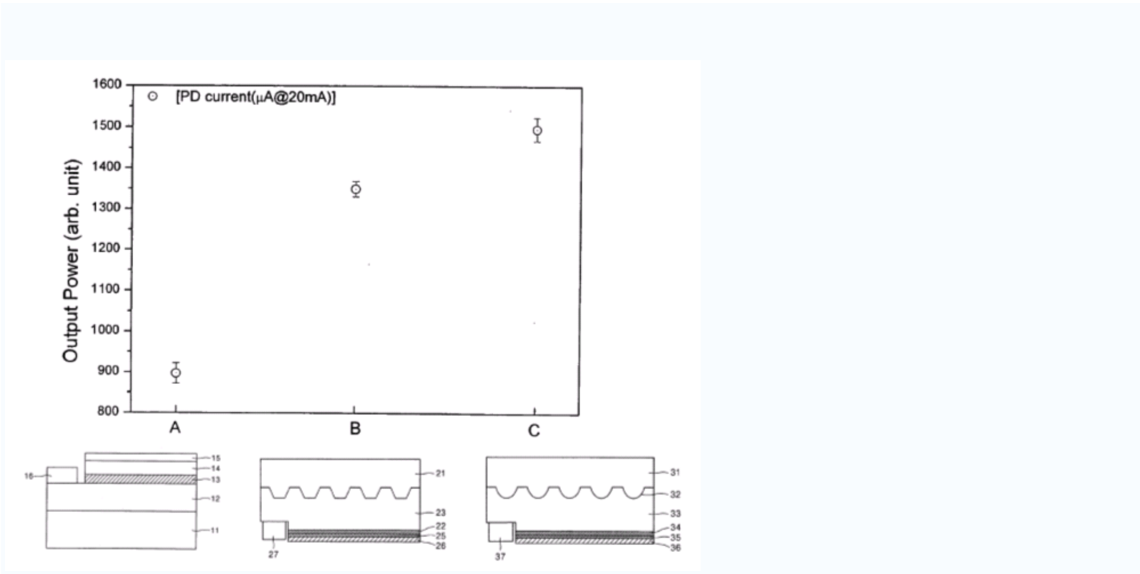


Figure 8 Light output power according to the LED design (A-conventional, B-competitor's design, C- proprietary design)

Above figures shows differences of performance between conventional device (designated in A), simple corrugation structure of sapphire (B), and curved corrugation structure of sapphire(C). Light extraction efficiency of case B in which the light-emitting device is formed on the simple corrugated substrate 50% greater than the case of A in which the light-emitting device is formed on the even substrate. The light extraction in case C (the ideas generated by TRIZ activity) in which the light-emitting device is formed on the curved substrate extracts light 60% more than in case A. In addition, light extraction in case C is approximately 10% than in case B. This is because circular corrugation of C device plays a role of an optical lens that changes the light path and at the same time reduces the defect density of the growing semiconductor crystal layer.

Even if some authors suggest similar concepts before[23] [24] [25] [26] [27], when curve patterned substrate was filed up as a patent, there were none with same concept.

When we tried making a solution for low extraction efficiency problem, 'inventive principles no.14. increasing curvature' gave an inspiration for the idea designated in C device. Once, we thought about 'lens type substrate', the domain experts suggested a way to fabricate such lens type substrate conveniently as following by general reactive ion-etching conditionized by 'design of experiement' methodology.

To enhance light extraction efficiency, it is necessary to change direction of light propagation from horizontal to vertical ways. Tapered macro structure was known as very effective method to change light propagation direction[28]. Lumileds changed this original concept in micro level and developed a technology called as buried micro reflector[29].

Buried micro reflector concept designated in the patent description was analyzed as following:

- **Objective/effect of the patent : increase light extraction efficiency**
  - **Component/unit process of Method level 1: By Decrease light propagation length owing to internal total reflection**
    - **Method level 2 : By Remove some part of light generation**
  - **Component/unit process of With mirror under the light generation part to re-direct the light toward the interface**

Usually, the original contents of patents are too difficult to understand the core concept of the patents because of several strategic reasons. In the beginning of patent design around, it is inevitable to make such original articles more understandable and divide several parts of patents into small concepts.

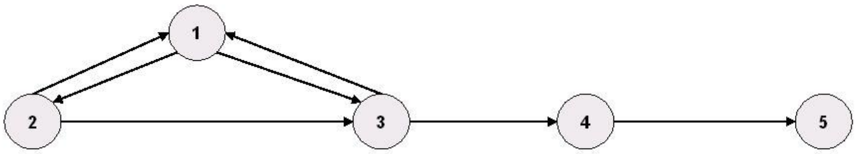
Only domain expert can remove "masked description" and identify "real description" from the claims

After constructing concept model of competing patent, we analyzed where the weak point exists. One sentence in the concept model attracted our notice.

"Removing some part of light generation".

If we do "remove some part of light generation", light generation area will be reduced, which means total generating light will decrease. We don't want such situation. Can we enhance light extraction efficiency without removing light generation part?

Table 3 problem model table: light trajectory modification



no	The reason to eliminate undesirable feature	Undesirable feature	Origin of undesirable feature	Transition action to eliminated undesirable feature and/or its origin	Child problem of known method or the reason why transition action can't be used
1	Efficiency is low	Extraction efficiency is low	Total internal reflection (phenomenon) between GaN and sapphire substrate (operating zone)	Buried micro reflector concept to change light propagation trajectory to vertical direction	Reduce light generation active layer → reduce total light generation
2					
3					

We could formulate our directed thinking as a form of technical contradiction.

- TC0: If we don't remove some part of light generation (conventional), light generation part is not reduced (good), but light extraction efficiency does not increase (bad).
- TC1: If we remove some part of light generation (USP6455878, Lumileds), light extraction efficiency increases because of decreasing light propagation length owing to total internal reflection (good), but light generation part is reduced(bad).

We could restate above contradictions as following during problem solving process.

- TC0': If there is no groove structure across the light generation part,), light generation part is not reduced(good), but light extraction efficiency does not increase(bad).
- TC1' : If there is groove structure across the light generation part(USP6455878, Lumileds), light extraction efficiency increases because of decreasing light propagation length owing to total internal reflection (good), but light generation part is reduced(bad).,

"Groove structure" is a product of removing some part of light generation part. According to the physical relationship, we could convert original statement to new one.

This problem model could be converted to physical contradiction automatically.

- PhC0': "groove reflector structure" across the light generation part should not exist → to reduce light propagation length to increase light extraction efficiency
- PhC1': "groove reflector structure" across the light generation part should not exist → to save light generation part

"Groove structure" should be removed as well as should not be removed. What could we do to resolve this contradictory situation? TRIZ suggests separation principles to separate such contradictory requirements by space, time, condition, scale. We asked following control questions to ourselves.

- ✓ Can we install such groove structure without removing light generation part?
- ✓ Can we install such groove structure before introducing light generation part to avoid removing light generation part? Bingo!

As concerning the idea about changing the mfg order of groove and light generation part, we could make a sense literally. Domain experts and TRIZ specialists generated following drawing immediately designated in Figure 10. It looks beautiful and has several benefits.

① Light generation part increases actually

② Non planar epitaxial structure of GaN has a potential to enhance inherent light generation efficiency.

③ Mfg complexity is lower than that of Lumileds.

Idea ignition principle was 13rd principle. Inversion: by inverting the manufacturing process, **groove was produced with increasing active layer**. Groove structure changes light trajectory effectively to avoid total internal reflection as well as increases light generation also.

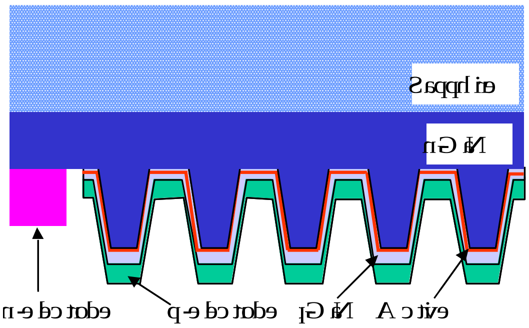


Figure 9 Non-planar substrate concept

Developing the concepts more elegant ways, SAIT proprietary concept was field up as United States patent in 2007[30] .Light extraction efficiency of non-planar substrate concept was 50% larger than that of conventional LED chip(plain chip).

Usually it takes a long time to realize suggested ideas. SAIT uses a special methodology to reduce such lead time of idea realization, which is called as six sigma. Six sigma is composed of succeeded procedure, statistical toolkit and many templates. Domain experts had-training of six sigma before. They were skillful to optimize several parameters according to statistical guidelines. With the feedback of experimental test, these ideas were able to realize more efficiently.

Summary

One of critical problem in conventional GaN LED system was analyzed by TRIZ methodologies. After resource analysis, total internal reflection between GaN and sapphire substrate was recognized as most serious source of the low extraction efficiency problem. Known solutions, i.e. transition action for the total internal reflection were critically surveyed by problem formulating table. Contradictions caused by transition actions were formulated and resolved with guidance of inventive principles which suggest conceptual guideline for technical contradiction. More than 20 useful ideas were induced by referring to principles of TRIZ. Many ideas have shown excellent performance for light extraction up to 60% increase. 2 of them were filed up as US patent and applied as one of most important technology for real LED chip produced by SEMCO, Inc.

Epilogue

This project was executed in May to September in 2003. More than 25 technical ideas were suggested. 2 of them were filed up as international patent. Applying one concept created by this project was introduced in real LED system produced by Samsung Electromechanics, Inc. With TRIZ thinking process, the problem "light extraction efficiency of LED is low" could be understood more thoroughly, the solutions for the problem could be induced more easily than without TRIZ. LED division of SAMSUNG Electromechanics could release brighter LED based backlight unit for cell phone in 2006[31].

In the end of the TRIZ activity, TRIZ consultants forecasted the near future of LED system. According to the pattern of increasing segmentation level, light extraction structure will be smaller and smaller to nano-level. Current papers and patents are dealing with such nanostructure in many boundaries[32]. Rapid realization of the suggested ideas was conducted by statistical assistance of six sigma methodologies.

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