

Global Technology Development in Solid State Lighting Technologies

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ABSTRACT

The determinants of successful development, commercialization and diffusion of solid state lighting (SSL) are not well understood particularly in a global context. Patent data provide one means to gain insight into corporate and national research and development activities. However, existing SSL patent analyses have focused primarily on United States (US) patents. This study analyzes SSL patents granted worldwide to measure the strengths of US, Japan, Germany, the Netherlands, South Korea, Taiwan, and China, nations all poised to play a key role in SSL's future. It shows a strong and growing role of corporate patent portfolios for firms headquartered in Asian nations. The data cover patents that were applied for and issued from 1937 to March 2009. Our findings suggest a stronger role of non-US organizations and individuals than had been reported in previous studies that focused only on US patents.

Keywords: solid state lighting (SSL); light emitting diodes; research and development (R&D); patents; companies; national innovation; international patent families; patent applications

1. INTRODUCTION

The United States (US) and other nations are counting on innovation in new technologies, particularly in the green and clean technology sectors, to create the jobs of the future and help stem global warming. Advances in solid-state lighting (SSL) technologies have the potential to have a significant impact on energy conservation and global warming as well as providing the foundation for 21st century industries. Already new SSL technologies are affecting several industry sectors – from traffic and architectural lighting to stationary and mobile displays used in computers, televisions, and mobile devices. The market is driven by technology and product development advances and by buyers who want products with greater functionality, styling, and energy savings.

But the determinants of successful commercialization and diffusion of SSL, as well as other energy saving technologies are not well understood, particularly in a global context. Missing from our national debate is an understanding of differences between the US, Japan, Germany, the

Netherlands, South Korea, Taiwan, and China, nations all poised to play a key role in the future of SSL. The global context is crucial because producers worldwide are competing to play a role in developing, manufacturing, and marketing solid state lighting technologies and products, with some nations promoting rapid development and adoption.

Our recent study, sponsored by the Department of Energy (DOE) and the National Science Foundation Smart Lighting Engineering Research Center, probes corporate and national research and development (R&D) in emerging light emitting diode (LED) and SSL technologies. The study, based on patents and applications filed with patent authorities worldwide, shows a greater role of firms and nations outside the US than has been noted in previous patent analyses that relied only on US patents. Because applicants tend to file predominantly in their home nations, studies based solely on US patents have missed large numbers of non-US applicants, overestimating the role of US inventors and firms.

Solid-state lighting has become a national priority for many of the world's nations. In addition to their motivation to save, many governments see it as an important generator of future employment and wealth creation. Substantial SSL and LED R&D has been ongoing for decades in the United States, Japan, Taiwan, Germany, and the Netherlands, and more recently two Korean firms, Samsung and LG, are emerging as powerhouses. China also has been moving from LED manufacturing into all levels of the value chain, from epitaxy and chips to lighting fixtures.^[1]

There is already a clustering of activities in the value chain across different regions of the world that have built on earlier investments in foundational materials, processes, and technologies. Moreover, a host of global players, large and small, draw on global supply chains in developing, designing, and assembling final products. Large global firms such as Philips, Siemens (including OSRAM Sylvania), and GE have operations around the world that are focused on research, design, and assembly. Even startup firms, like Color Kinetics (purchased in 2007 by Philips), were born global, buying devices and assembling their architectural lighting products in Taiwan and the Chinese mainland.

2. THE DATA

This study assesses global technology patterns and trends by measuring LED and organic light emitting diode (OLED) patenting worldwide for all nations in which relevant patent data can be obtained. Business and research organizations in the US are compared to their foreign counterparts, and patents applied for or granted in the US (at the US Patent and Trademark Office) are compared to patents applied for or granted in nearly 70 other nations (at their respective patent offices). This includes all nations in which substantial SSL, and LED and organic light emitting diode (OLED), activity seems to be occurring, including the United States, Japan, Taiwan, South Korea, and China. Specific areas of technology such as fundamental components, displays, and lighting are compared.

2.1. Dataset Construction

To document and analyze SSL R&D, a systematic source of evidence is needed. This evidence must span the range of people, companies, institutions, and nations involved in SSL, and provide at least an indicator of their involvement in relevant R&D. Two types of evidence are available fairly consistently across the players in SSL R&D: publications and patents. Of the two, publications are a better measure of basic R&D and tend to come from the university sector, whereas patents are a

better measure of applied R&D and tend to come from businesses. Patents are therefore the focus of this study. Patents granted from patent authorities worldwide are considered, to avoid potential US-centric biases that might result when examining data only on US patents. Patents stem from applications, which provide leading-edge evidence on R&D activity, and hence applications data are used here to understand the most recent trends. Patents' poor cousins, utility models, are granted by many nations (not the US) for typically six years' rights with a much-simplified application process, and data on granted utility models also were considered to provide further evidence on R&D activity for which less formal protection is sought. All this evidence had to be built up in a systematic database.

2.1 Primary data source

We began with data from the European Patent Office's (EPO's) "EPO Worldwide Patent Statistical Database." The EPO collects patent data from national patent offices worldwide and places it on its *esp@cenet* Internet search system, which is publicly accessible on the Internet. The Worldwide Patent Statistical Database consists of bibliographic data drawn from *esp@cenet*, along with data on some types of publications not shown in *esp@cenet*, for all patent authorities and time periods in which data are available. The data include, ideally, the numbers, titles, abstracts, technology classifications (national and international), applicant names, inventor names, citations, and various types of publications for each patent or utility model applied for. In practice, such data are a recent creation, so the availability of abstracts, citation data, title translations, and other desirable features varies across national patent offices and time. Missing data are common even for the United States Patent and Trademark Office, for which for example citations data are available only sporadically in many years including recent years. Hence abstracts and citations data, which are rarely available in the full dataset, are not exploited here. The data identify one or more publications for each patent or utility model application, using a series of nation- and time-specific codes for the type of publication. After combing through these codes, we ruled out applications that only had publications indicating translation of another patent office's documents. We also categorized codes that indicate an application was granted as a patent or as a utility model. The data cover about ninety nations' patent authorities worldwide, including all of the nations most active in LED R&D and patenting (such as the US, Canada, the European Community plus individual European nations, Japan, Korea, Taiwan, China, and Australia). These individual patent authorities continually supply information to the EPO, which puts the data into useable form and loads it into *esp@cenet*, then carries out several more cleaning steps

2.2 Search strategy

Within the EPO dataset, we identified relevant patents based on both application titles and international patent classification (IPC) codes. Titles in the EPO dataset mainly have been translated to English language, but a fraction of European-language titles remain in their original European languages. When we searched titles we therefore focused our efforts on English-language searches, but we used rudimentary non-English-language keywords and international patent classification codes to identify relevant applications that had non-English-language title data. A small percentage of applications in the data have no title data available, and a small percentage have no IPC code data available. Searching by both methods allowed us to identify relevant applications that lacked one of these types of data in the EPO Worldwide Patent Statistical Database.

Title search strings were identified through a succession of investigations of likely terms to identify LED- and SSL-related applications. We also identified relevant search strings by examining all applications by LED-related firms, that is, firms whose activity has been focused narrowly on LED- (and SSL-) related applications. These firms included Cree, Color Kinetics (now Philips Color Kinetics), and Nichia. We also investigated possible terms by checking titles of patents designated in US class 362/800, the US Patent and Trademark Office's light-emitting diode cross-reference art collection. Applications that matched any one or more of our title keyword strings or IPC codes were included in the database.

Search results were checked to ensure that they did not erroneously identify any substantial percentage of off-topic applications. One of our title search terms, "LED", did yield a small percentage of off-topic applications, because titles might use the verb "led" for example for a pipe "led through" a cylinder wall or a wire "led into" a circuit. Therefore for "LED" only we examined all titles that used this word to ensure that they were not misuses of the word "led", and we removed from the data these irrelevant applications.

Title searches required whole words to be identified (separated by spaces or non-alphanumeric characters such as punctuation marks). An "(s)" or "(n)" denotes an optional s or n, and an asterisk allows any characters. Searches were not case-sensitive.

The following English-language keyword strings were used to search titles: "light emitting diode(s)", "light-emitting diode(s)", "LED(s)", "OLED(s)", "PLED(s)", "L.E.D.(s)", "LED-based", "semiconductor light emitting", "semiconductor light-emitting", "semiconductor light emission", "semiconductor lighting", "semiconductor lumin*", "solid state lighting", "solid-state lighting", "solid state light(s)", "solid-state light(s)", "solid state lamp(s)", "solid-state lamp(s)", "micro-LED(s)", "light emitting die(s)", "light-emitting die(s)", "luminescent diode(s)", "light emittingdiode(s)", "lightemitting diode(s)", "lightemittingdiode(s)".

The following basic non-English-language keyword strings were used to search titles: "lichtemittierende Diode(n)", "Leuchtdiode(n)", "diode(s) luminescente(s)", "diodo(s) electroluminoso(s)", "diodo(s) luminoso(s)", "diodo luminescente", "diodi luminescenti", "luminescente diodo", "luminescenti diodi", "diodos emissores de luz", "diodo(s) emitindo-se claro(s)". These non-English language search terms covered the non-English languages in which there are, with any substantial frequency, non-English titles in the EPO dataset. Asian titles never appear in the EPO dataset; all titles for patents originating in Asian patent offices have either been translated to English or (generally for some quite old applications) lack title data in the EPO dataset.

Table 1. International patent classifications searched for with frequencies and descriptions

Category	Number of applications	Brief informal description
H01L33/00	79,672	Semiconductor devices for light emission, including manufacture and details thereof
H05B33	63,003	Lighting – Electroluminescent light sources
G09G3/30	14,977	Circuits for readable displays using electroluminescent panels
G09G3/32	9,861	As G09G3/30, using semiconductors
G09F9/33	8,718	Pixel-based displays using semiconductors
H01L27/15	6,233	Solid-state circuitry incorporating semiconductor light-emitting devices
G09G3/14	2,738	As G09G3/32, but for displaying a single character

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Table 2. Percentage of applications in various groups caught by search

Group of applications	Number of applications	Percent caught by search
Filed by Color Kinetics	272	49.6%
Filed by Cree	1885	41.3%
Filed by Nichia	3373	58.1%
US class 362/800	1775	44.8%

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We also included applications that were classified in any of several IPC code categories. Codes used were chosen to be narrowly focused on LEDs or semiconductor electroluminescence. The codes searched for use (almost entirely) the 2006.01 advanced version of the international patent classification system. The codes searched for, in order of frequency of occurrence, are: H01L33/00, H05B33 (all subgroups), G09G3/30, G09G3/32, G09F9/33, H01L27/15, and G09G3/14. This would catch some applications related to lasers, so we partially screened out applications most directly related to lasers by ignoring resulting applications that include “laser(s)” in their titles, unless those applications were also identified based on title searches. The number of applications (granted or not, for patents or utility models) classified as having each of these codes is listed in Table 1. Some applications had more than one of these codes, since the average application in our data had 3.6 IPC codes.

This approach does not identify all LED- or SSL-related applications, but does identify a large percentage. Applications whose titles and classification codes do not satisfy the search methods used here could still be applicable in various ways to LEDs or SSL. To better understand the frequency with which relevant applications were caught by the search procedures used here, we analyzed all applications filed by three firms that specialize in aspects of SSL (Color Kinetics, Cree, and Nichia) as well as all applications catalogued in US class 362/800, the light-emitting diode cross-reference art collection, as of the most recent available EPO data at the time of this study. Table 2 shows the result of this check. Approximately half of all relevant patents seem to be identified by the search methods used, with some variations in this fraction between different companies, nations, and types of information sources. This substantial fraction, and its comparable size across the groups, is reassuring that meaningful analyses can be carried out using the dataset developed here.

2.3 Nationality data and sampling procedures

When analyzing inventors' nations of residence, as well as applicants' nations of address, the EPO Worldwide Patent Statistical Database causes two problems. First, the data contain frequent gaps in available data on the nations of residence of inventors. These gaps are most frequent for particular national patent offices and particular nations of residence, and differ in frequency by time period, patent versus utility model applications, and granted versus non-granted applications. As a result, ignoring the gaps and calculating results based on available data would yield biased findings. For example, the inventor nation is often missing for patent applications with Japanese inventors. If one blindly computed the percentage of patents with Japanese inventors based on available data, the answer would be erroneously low, suggesting that Japanese inventors played a much more minor role than their real percentage of contributions to applications.

Second, mainland China and Taiwan often are coded identically. If this problem were not noticed, an analyst attempting to tell apart mainland China and Taiwan might conclude that mainland China's role in SSL R&D is substantially greater than its actual role. The issue arises frequently for applications filed with the State Intellectual Property Office of the People's Republic of China, but also arises sometimes for applications filed in other nations.

To deal with these problems, we looked up and compiled by hand the nationality data for a sample of applications with missing inventor locations, and for a sample of applications in which the location was recorded as China. The modern survey research methods that we used involved subdividing the patent data into "strata" (by language, technology classes, whether patents were granted, etc.) and collecting data on randomly selected applications in each stratum. Statistical methods designed for surveys were applied to the resulting data to understand the range of error in our findings; in all cases the resulting range of error was small. To collect the data, our team of research assistants looked up facsimile images of published documents and read the inventor nations from these documents. Since these documents were published in Japanese, Chinese, Korean, and various European languages, the team was chosen to include persons fluent in many languages. We were unable to obtain a research assistant fluent in Cyrillic languages, leading to some undercounting of applications filed in Russia and nearby nations, probably most frequently by inventors in those nations. Data entry was double-checked by having some of the research assistants collect data for the same applications twice; the error rate in these cases was minimal. Given the considerable expense and effort required, we reduced costs by not looking up the nations of applicants when data were missing, but only of inventors, and then assuming that the distribution of nations in the two cases of missing information was the same – a seemingly reasonable assumption judging from initial investigations on a subset of the data.

Nationality data were compiled in this way only up to the September 2008 edition of the EPO data, since the subsequent edition was finished by the EPO only in June 2009 shortly before our analyses were completed. Hence analyses of nationality data here exclude the roughly six months of information between those two editions, although information from the June 2009 edition is used for analyses of companies.

By far the largest number of applications in the data, and by far the largest number for which inventor locations were missing, was for applications filed with the Japan Patent Office (JPO). To reduce the data collection effort, we obtained massive data files in Japanese language regarding nearly all applications filed with the JPO over an extended period. The data do not match readily to

the EPO data, but Dr. Jun Suzuki of the Graduate Institute for Policy Studies in Tokyo kindly created a matching table that allowed us to match between the two datasets. This allowed us to match many of our Japanese language applications to the JPO data. The data include the addresses of inventors in Japanese language, and we programmatically extracted the nation names from these addresses. Our algorithm worked very effectively as judged by applicant nation data available from the JPO, since our conclusions almost always agreed and in the few cases of differences our algorithm much more often (and statistically significantly) outperformed the JPO classification assuming the JPO's address data are correct. When all inventors were from the same nation (which is almost always true), we used this information to determine the nation of residence of all inventors. This matching and nation determination procedure provided nation of inventor residence information for approximately half of all Japanese applications with missing inventor locations, substantially reducing the data collection challenge.

Among 47,839 applications with missing inventor locations, we hand-collected information on 9,804 applications. Among 7,424 applications with inventor locations denoted as China, we collected information on 5,278 applications. This gives quite small margins of error for nations with substantial numbers of patents, granted applications, or applications respectively.

2.4 Identification of technology sub-domains

We classified each application in our data into zero or more technology sub-domains. Our classification of technology types is based on both international patent classification (IPC) codes assigned to each application, and the title of each application. A minority of applications have no IPC data or no title data, though all have at least one of the two, and in these cases we used the available title or IPC data to classify them as usual, albeit with less opportunity for classification into any given category.

Our overall category, All, includes all applications in the data. If one wishes to focus on general illumination applications, it helps to filter out the most frequently occurring other technologies involving LEDs: displays, printers, and scanners. Categories created for Displays and (not used here) Printers & Scanners identify applications involving these technologies. Removing display, printer, and scanner related applications from All yields the category All But Displays, Printers, and Scanners. This category includes LEDs and related materials, circuitry, and manufacture as well as the use of LEDs in myriad applications. Indicator lights and some unusual applications remain. Unfortunately there is no easy way to classify applications according to the color or intensity of light emitted.

Fundamental technologies including LED design, materials, packaging, methods of manufacture, and control circuitry make up a large part of the data. To attempt to systematize analysis of these fundamental technologies, rather than applications, we therefore created a Fundamental category based on a broad range of IPC codes.

A purist might attempt to focus on applied general illumination lighting technologies by removing from consideration any application that in any way is not lighting, including fundamental technologies. This reductionist applied focus yields a category denoted Lighting, with very small numbers of applications, but largely free of contamination from other sorts of technology. This category may be useful to get an idea of the locus of innovative activity in applied general illumination lighting.

Two further categories are used here. Organic consists of applications involving organic chemicals, and Vehicle consists of applications explicitly relevant to vehicles.

Table 3 lists the categories along with their formal definitions. The definitions rely on IPC- and title- based classifications reported in Tables 4 and 5 respectively. Applications matching any item in a list of IPC codes or title keywords are included. Title searches were not whole-word searches (in contrast to title searches used to identify the overall dataset) and were not case-sensitive. Some title search strings included spaces or the carat (^) marker that indicates that the string must appear at the start of the title. For the category Organic, we follow the practice of Boyack et al. (2006) of excluding applications that include the title term “metal organic”, a minority of which pertain to chemical vapor deposition equipment.^[2]

2.5 Other aspects of data preparation

Other data analysis work necessary included matching of alternate, misspelled, and changed company names; determination of company ownership and acquisition; codification of types of documents published by patent offices; development of 10,000 lines of complex data programming code; and creation of thorough programmatic checks to ensure correct treatment of the data.

3. FEATURES OF THE PATENT DATABASE

The dataset consists of 185,852 applications filed in 68 nations. The earliest SSL or LED related applications appear to have been filed by the mid-1930s, and the latest on the fourth day of December 2008. The most recently granted patent in the data was granted on the fifth day of March 2009 (it was applied for on April 12, 2002 in Germany). There are 59,633 granted patents. The data also cover 12,499 granted utility models and (in a few cases) other receipts such as communist-style inventor’s certificates. As noted below, actual counts used hereafter are lower than these numbers, since members of international “patent families” are not double-counted. There are more than twice the number of applications for patents or utility models than there are actual patents or utility models

Table 3. Technology category definitions

Category	Definition (subset of dataset)
All	All applications
All but displays, printers, and scanners	Any application not in any of the IPC categories: Display Projector PrintScan PhotoPrinter FundSemiPl, and not in any of the title categories: DispPrintScan Backlight
Lighting	Any application in the overall category All But Displays, Printers, and Scanners, that is also in IPC category: Lighting or in any of the title categories: Lamp WhiteLight, but only if it is not in title category Indicator and not in overall category Fundamental
Fundamental	Any application in any of IPC categories: FundOptics FundElectr FundSemic FundComm FundManuf FundChem
Displays	Any application in any of the IPC categories: Display Projector FundSemiPl, or in title category: Display
Organic	Any application in IPC category Organic or in title category Organic, but not in title category MetalOrganic
Vehicle	Any application in IPC category: Vehicle

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Table 4. IPC-based categories used in technology category definitions

Category	Definition (IPCs included) and comments
Lighting	E01C17 E01F13 E01F9 F21 G08G G09F13 H05B31-43 [Primary lighting applications.]
Display	G09G3/03-38 G09F9 H04N3-17 G09G5 G04G9 G06F3/147 G06F3/033
Projector	G02B27/18 G03B21 H04N5/74 H04N9/31
PrintScan	B41J G03G15 G06K15 H04N1 B41 G06K7 [Printing and some scanning uses of LEDs/OLEDs/PLEDs.]
PhotoPrinter	G03B27
Vehicle	B60-64
FundOptics	G02B G02F
FundElectr	H01J H01R H01S H03K H05K
FundSemic	H01L21 H01L23 H01L25 H01L29 H01L31 H01L51 G03F G11C, also H01L33/00 if that is the only IPC listed on the patent [Classify based on H01L33/00 only if it is the sole IPC for an application because many applications list this simply to indicate an LED is involved.]
FundSemiPl	H01L27 [Fundamentals of semiconductors for devices with a plurality of components, most of which pertain to displays and arrays, which are rarely pertinent to present-day general illumination approaches.]
FundComm	H04B10 H04M H04Q [Communications including telephonic and light-beam.]
FundManuf	B01 B03 B04 B05 B07 B08 B21 B22 B23 B24 B25 B26 B27 B28 B29 B30 B32 B42 B43 B65 B66 B67, BUT NOT B01D35-53 AND NOT B01J [Manufacture of LEDs/OLEDs/PLEDs mainly, but with some applications mixed in. Excluding B01D35-53 and B01J rules out application-related IPCs, notably B01J which is mostly applications to photocatalysis.]
FundChem	C07-08 C09C C09K11 C01 C02 C03 C04 C09 C12 C22 C23 C25 C30
Organic	C07 C08

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Table 5. Title-based categories used in technology category definitions

Category	Definition (keywords included)
DispPrintScan	display screen panel matrix array pixel printhead “print head” printer scanner “ head” “head ”
Display	display screen panel
PrintScan	printhead “print head” print-head printer scanner “ head” “head ”
Indicator	indicator indicating “status led”
Backlight	backlight “back light”
Lamp	lamp lighting luminaire luminary bulb illuminat leuchsystem lumen luminosity beleuchtung
WhiteLight	white
ColorLight	color “ red” “red ” orange yellow green blue indigo violet purple
Vehicle	vehicle vehicular automobile automotive motorcycle motociel
Organic	organic “ oled” “^oled” oleds pled plects polym monom ligand hydroxy macromol organics
MetalOrganic	“metal organic” “metal-organic” metalorganic
Packaging	packag capsula

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granted. We present some of the main data on applications and utility models in this section and focus most of the discussion in later sections on granted patents, which provide a stronger measure of high quality innovation.

When counting applications for patents or utility models, several considerations arise. Common mistakes of interpretation are discussed below, to avoid errors when examining data reported herein. International patent families are explained, along with our treatment of them. Counting methods are also explained, including why fractional patent counts often result.

3.1 Mistakes of interpretation to avoid

Several common mistakes should be avoided when examining applications and patents data:

- *Decreases in counts in recent years need not indicate a slowdown in patent-related activity.* There are substantial (legally imposed) time delays between when an applicant files for a patent or utility model and when details of the application are made public knowledge. Nations also differ in how rapidly they make available information to the EPO for inclusion in online data and in the EPO patent database that is our initial information source.
- *Granted patents and utility models here are reported not by grant year but by application year.* The focus on application years makes it possible to analyze when R&D activity occurred, rather than how long it took for a national patent office to approve an application.
- *Company-specific counts do not represent all of a company's SSL- or LED-related patents.* Typically the data used here seem to capture about 50% of LED-related applications, and it is possible for this figure to vary by firm.
- *Counts are not free of error.* Small variations in the counts are likely based on whether or not particular applications happen to be included in the data. If the intent is to measure a company's or nation's underlying R&D activity, moreover, there are both systematic variations in the propensity for a company's or nation's personnel to choose to file for patents or utility models, and random variations in whether or not a potential application is in fact filed. Random fluctuations are most likely to be important for counts of 10 or fewer, because the changes in apparent R&D output then tend to be large relative to the total count.
- *All patents are not equal.* The distribution of monetary gains achieved from patents is well known to be highly skew, with a few patents accounting for the bulk of the value. Therefore the counts used here are useful to gauge the extent of R&D activity, but not the extent of R&D success. Attempts to measure the value of patents, or at least whether patents have some minimal threshold value, are sometimes based on citations received or whether renewal fees are paid (in nations where patents must be renewed for a charge), but unfortunately the requisite data are not available for most of the dataset used here. An alternative, the development of international patent families, will be discussed below.

Despite these cautions that must be exercised when interpreting patent-related data, the information reported here provides valuable evidence about who is carrying out SSL-related R&D activity in what parts of the world.

3.2 International patent families

Rights for an invention are often applied for in multiple nations, such that a nearly identical application is translated into each nation's working language and legal documents to seek to obtain patent (or utility model) rights are filed with each nation's patent authority. The set of near-identical applications filed for the same invention with multiple patent authorities is termed an "international patent family." Families are identified by European Patent Office personnel according to two alternative definitions, DocDB and Inpadoc families, and here we use the Inpadoc definition of international patent families. Families may also include more than one application filed in the same

nation, because applications may go through a series of legal stages before being ready for potential granting of rights.

Applications from the same international patent family are here counted only once. This avoids double-counting of R&D on the same technology. However, it is well known that patents in international families tend to have greater value than patents not in international families. In fact, estimates suggest an average increase in patent value of about 40% per additional nation.^[3] We therefore in some cases report data restricted to applications in international families.

3.3 Division of credit across applicants and inventors

A given application may have multiple applicants and inventors, sometimes based in different nations. To avoid double counting of R&D activity, we therefore divide credit equally among all inventors and applicants on each application. This results in fractional counts that more accurately reflect SSL R&D activity.

3.4 Applications, grants, and patents

Applications here denote any filing with a national or regional patent office with the intent to obtain patent rights, utility model rights, or in communist nations, formal recognition such as inventor's certificates. Typically analyses here focus on granted patents. In one table herein we consider all grants, including utility models and (much rarer) inventor's certificates. Our total count of applications in the data is 120,728, with 50,356 grants of which 38,625 are granted patents. Utility models, as noted earlier, are easy-to-obtain variants of patents that last typically six years and are available from some nations' patent authorities (not the US).

3.5 Frequency of technology sub-domains

Applications in the database were classified into technology sub-domains as noted in section 2.4. Out of the 120,728 applications in the data, Table 6 indicates how many applications fall within each pair of technology sub-domains. Some sub-domains are exclusive from others. Applications classified in the sub-domain labeled All But Displays, Printing, Scanning never appear in the sub-domain labeled Displays. Likewise, applications classified in Lighting never appear in Fundamentals or Displays. Other sub-domains overlap. Of the 18,908 applications in Lighting, 1,913 are also in Organic and 879 are also in Vehicles. Similar overlaps can be read from the table for other pairs of sub-domains.

Numbers on the diagonal of Table 6 indicate how many applications fall within each sub-domain. The largest sub-domain is All Except Displays, Printing, Scanning with 76,513 applications. The second largest sub-domain is Fundamentals with 74,893 applications. The smallest sub-domain considered here is Vehicles, with 2,057 applications.

Since the primary focus here is on granted patents, Table 7 presents similar data on sub-domains restricted to granted patents. Not surprisingly the number of patents is much smaller than the number of applications in each sub-domain. The largest sub-domain among patents is Fundamentals with 25,425 patents, followed closely by All But Displays, Printing, Scanning with 24,304 patents. The smallest sub-domain is Vehicles with only 587 patents included in the dataset.

Table 6. Frequency and cross-categorization of applications by technology sub-domains

Sub-Domain	All except displays, printing, scanning	Lighting	Fundamentals	Displays	Organic	Vehicles
All except displays, printing, scanning	76,513	18,908	53,901	0	9,945	1,436
Lighting	18,908	18,908	0	0	1,931	879
Fundamentals	53,901	0	74,893	18,604	12,496	296
Displays	0	0	18,604	39,014	7,444	517
Organic	9,945	1,931	12,496	7,444	17,682	23
Vehicles	1,436	879	296	517	23	2,057

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Table 7. Frequency and cross-categorization of patents by technology sub-domains

Sub-Domain	All except displays, printing, scanning	Lighting	Fundamentals	Displays	Organic	Vehicles
All except displays, printing, scanning	24,304	5,003	18,498	0	3,449	411
Lighting	5,003	5,003	0	0	534	264
Fundamentals	18,498	0	25,245	6,079	4,316	107
Displays	0	0	6,079	12,869	2,713	135
Organic	3,449	534	4,316	2,713	6,244	7
Vehicles	411	264	107	135	7	587

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3.6 Activity by patent authority

Most previous studies of patenting in SSL have focused on patents filed in the United States, potentially over-representing the strength of English-speaking nations, particularly the US, and under-representing other nations. Boyack et. al. recognized this limitation in their 2006 analysis of international trends in SSL.^[2] Focusing on patents applied for and granted in patent authorities around the world, as in our study, is likely to lead to a better understanding of knowledge creation worldwide.

About four times as many LED-related patent applications have been filed with the Japan Patent Office (JPO) compared to the next highest number filed with the US Patent and Trademark Office (USPTO). Reliance on USPTO data alone would ignore the large number of applications applied for in Japan, many filed for by Japanese companies. When granted patents rather than applications are used as the measure, the apparent gap between the US and Japan is much smaller, with only about 10-20% more patents granted in Japan than in the US. In fact this comparison is for many purposes more accurate. Japanese patent law before 2001 gave companies seven years from filing before they had to decide whether to pay for a full evaluation, whereas after 2001 the maximum time lag was shortened to three years. In other ways as well, the Japanese patent system has moved closer to the US patent system over time.^{[4],[5],[6]} Focusing on patents rather than applications helps to make

counts more comparable between the two nations in all years. An alternative also used below is to consider only applications filed in multiple nations.

We looked further into the issue of whether multi-national patent data are needed to achieve unbiased counts, by analyzing the nation-specific makeup of the patent portfolios of LED companies in Japan. For example, we compared data on Nichia's semiconductor patents received from the JPO to those received from the USPTO and other patent authorities around the world. Nichia has three times the number of granted patents in Japan compared to the US, judging from their public list of semiconductor patents. If Nichia is typical of other non US headquartered firms – as turns out to be the case – considering only USPTO patents would undercount the intellectual property of firms not headquartered in the US and potentially result in a nation-specific bias. While it is sometimes argued that the US market is sufficiently large that it should attract patent filings for all valuable technologies worldwide, it is curious that in fact many firms doing serious R&D choose to file for patents primarily in their home nations. There are several potential reasons for this home-nation tendency, such as using patents as a means to show activity rather than to gain rights or using patent rights primarily as competitive tools against firms also active in the same nation which are perhaps most likely to sell similar products in related geographic markets. Whatever the reasons, the evidence suggests that to avoid potentially serious nation-specific biases, data from patent authorities worldwide are needed.

4. LEADING COMPANIES

4.1 All LED Technologies

To examine the performance of companies in LED technology, one can examine counts of companies' LED-related patents. Two alternative metrics can be used. First, applications can be used instead of granted patents, to consider recent activity of companies before patents had time to be granted. Second, relatively high quality patents or applications can be considered, by restricting analysis to patents granted in, or applications applied for in, multiple nations. Companies' patents and applications are compared below by examining first all granted patents, then only multi-nation granted patents, and finally applications.

Figure 1 shows, using all LED patents granted, the performance of firms for the two half-decades 1999-2003 and 2004-2008. Years pertain to the dates when the patents were filed, not when they were granted, in order to reflect better the actual times of R&D activity. Over the first half decade, Seiko led, with Philips, Semiconductor Electronics Laboratory (SEL), Sharp, Sanyo, Matsushita, and Siemens close behind. Samsung and Kodak had almost the same number of granted patents, followed closely by Nichia and Toshiba. Other Japanese firms, and Taiwanese and US-headquartered firms, trailed.

In the subsequent period beginning in 2004, the number of patents granted to Samsung grew very quickly, exceeding all other firms almost four times over. Matsushita, Philips, Kodak, Seiko, Sharp, and Siemens were consistently strong in these time periods. LG and AU Optronics made large strides from 1999 to 2004, receiving some of the largest numbers of patents. During 2004-2008 some new players began to have significant numbers of LED patents, including Korea's Seoul Opto Device and Seoul Semiconductor, Taiwan's ITRI and Formosa Epitaxy, and in the US, Kodak, 3M, GE, and Cree.

In Figure 2, patents granted in at least two nations are used as the metric, with the count being the number of such multi-nation patent families. When this is used as the metric, Samsung again emerges as the leader in the most recent five-year period, but much less so than when counting all granted patents. This reflects the fact that although Samsung had many multi-country patents, it also filed large numbers of patents in Korea alone. Seiko fell from first place in 1998-2003 to a close second place in 2004-2008. Philips and Siemens were near the top of the list in both periods, while the other traditional lighting firm, GE, ranked much lower. Sanyo remained ranked fifth, Sony fell from sixth to seventh place, and the Taiwanese firm AU Optronics moved from 22nd to eighth place.

In Figure 3, using applications, Samsung again stood out as the dominant firm in the most recent five-year period. The ranking of the top 29 companies changed modestly between the two five-year periods. Sony, Matsushita, Seiko, and LG were among the leaders in both years, while Sharp fell from fourth to tenth place between the two time periods. The exception, again, was Samsung, which moved from seventh place to being the clear leader, with over 4,000 applications during 2004-2009.

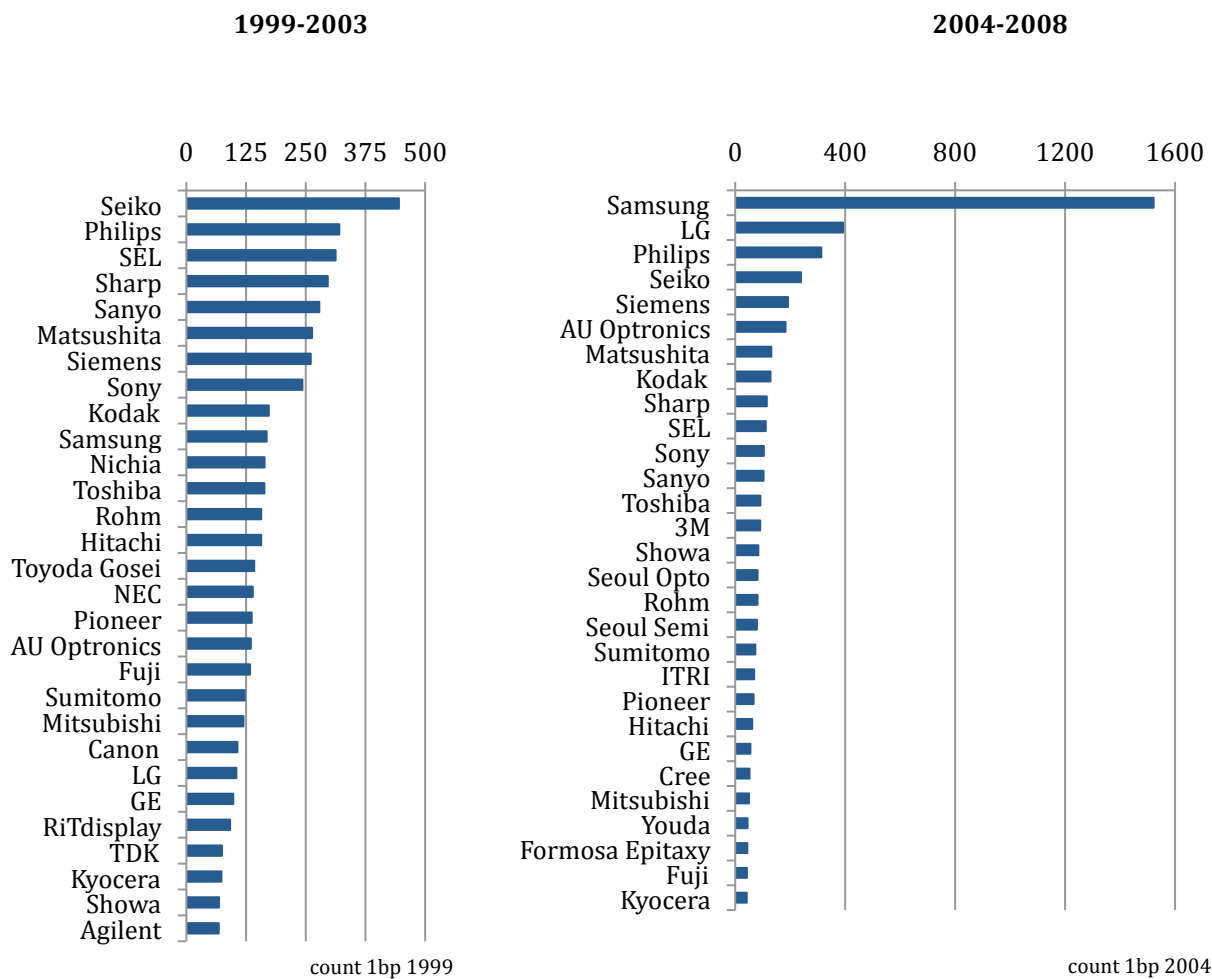


Figure 1. All LED patents granted to top firms filed in 1999-2003 and 2004-2008 (Copyright ©2009 Kenneth L. Simons, reproduced by permission)

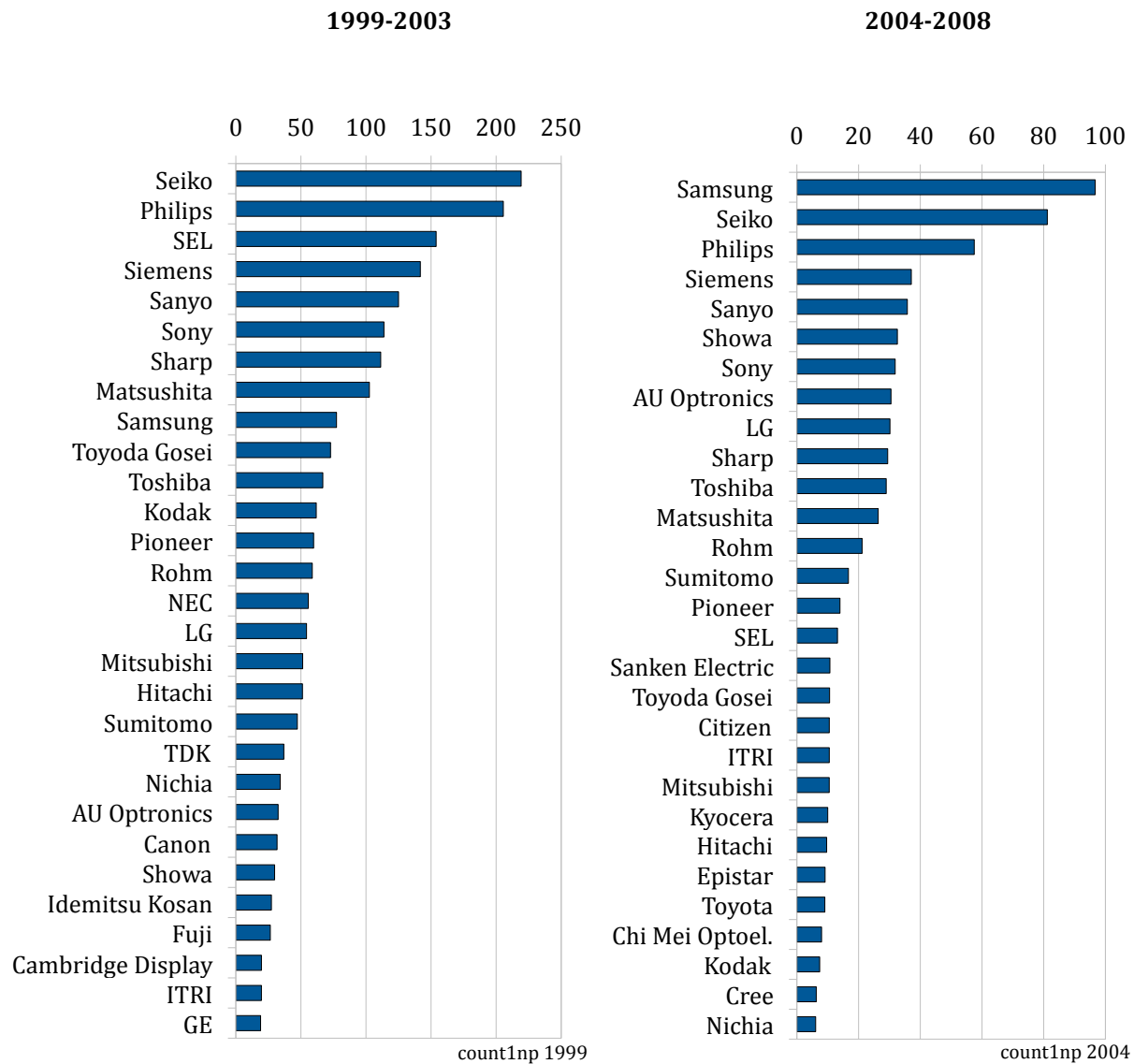


Figure 2. LED patents granted in two or more nations to top firms, filed in 1999-2003 and 2004-2008 (Copyright ©2009 Kenneth L. Simons, reproduced by permission)

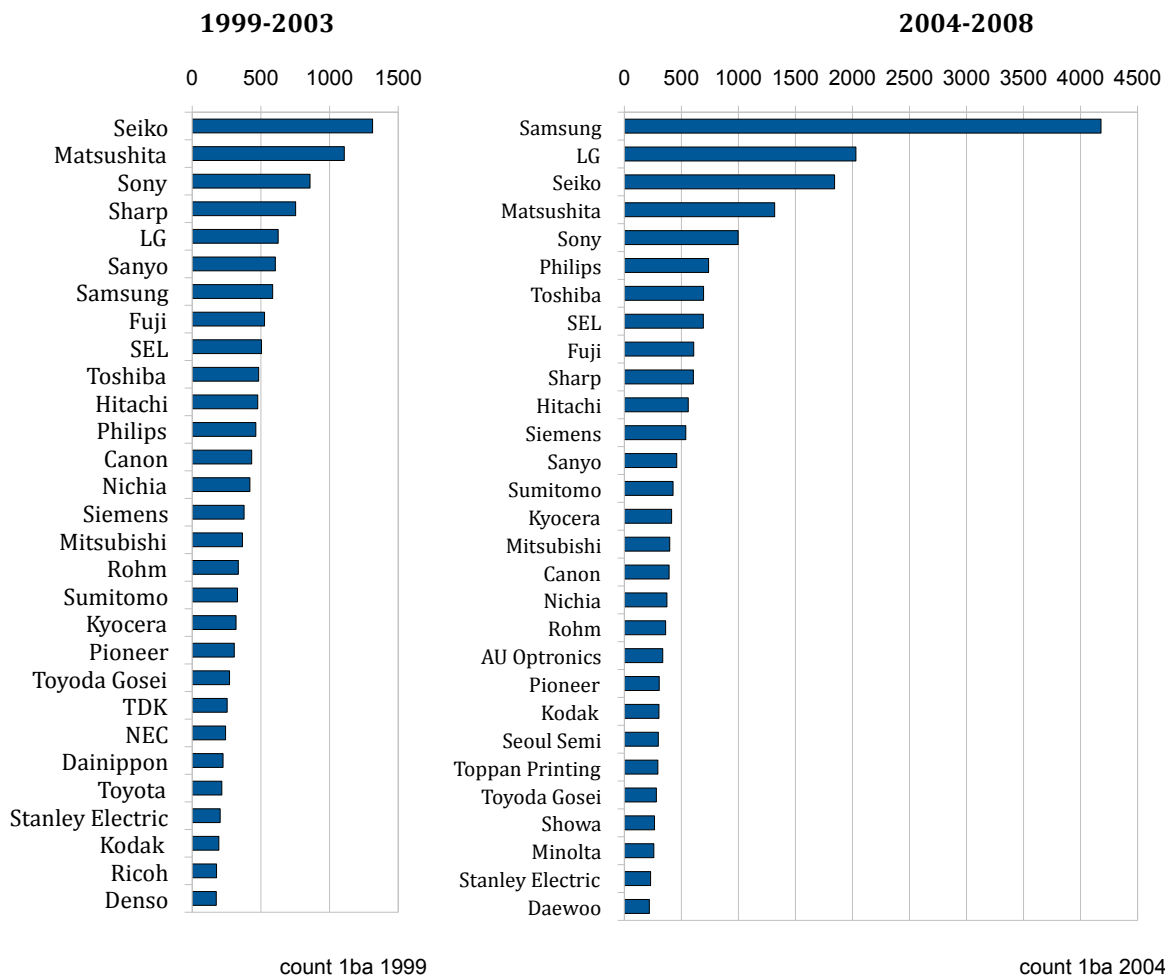


Figure 3. LED applications of top firms filed in 1999-2003 and 2004-2008 (Copyright ©2009 Kenneth L. Simons, reproduced by permission)

4.2 Nations in Which Companies Received Patent Rights

Table 8. Leading companies' patents granted by patent authority

Company	Number of patents by authority in which patents were granted											
	JP	US	TW	CN	KR	EP	GB	DE	FR	IB	CA	IT
Samsung	110	385	30	211	1324	27	14	31	5	0	1	0
Sharp	1028	451	95	97	14	74	48	59	8	0	3	0
Matsushita	915	381	82	80	6	54	61	38	47	7	14	5
Philips	70	641	132	120	17	229	128	68	178	355	35	38
Siemens	60	555	173	96	2	181	100	327	69	1	11	13
Seiko	595	305	300	258	6	62	15	0	0	0	1	0
Toshiba	629	357	85	59	41	45	34	13	8	0	8	7
NEC	676	147	44	31	9	53	13	7	3	0	11	0
Sanyo	449	223	159	106	2	12	0	2	0	0	2	0
Mitsubishi	414	333	28	33	13	44	27	25	18	0	9	0
LG	25	141	40	89	391	16	20	2	10	0	0	0

Company	Number of patents by authority in which patents were granted											
	JP	US	TW	CN	KR	EP	GB	DE	FR	IB	CA	IT
Sony	339	354	127	84	6	38	18	4	10	0	9	6
Hitachi	352	237	66	44	11	25	27	27	11	0	0	0
SEL	199	341	151	154	9	10	0	0	0	1	0	0
Rohm	385	198	62	30	13	10	6	3	2	0	1	0
Kodak	32	500	54	28	1	67	4	1	4	0	7	0
Nichia	501	92	30	64	12	13	1	0	0	0	9	0
Fujitsu	333	100	15	9	7	29	4	5	5	0	1	0
Sumitomo	310	152	52	41	19	50	21	1	2	0	10	0
GE	2	409	10	13	0	6	64	13	28	1	12	0
AU Optronics	5	91	193	113	0	1	0	0	0	0	0	0
Canon	170	210	12	32	6	53	2	5	1	0	4	0
Kyocera	286	20	18	9	0	1	0	0	0	0	0	0
Pioneer	194	175	45	12	0	20	1	0	0	0	0	0
Toyoda Gosei	227	204	59	38	4	14	3	6	0	0	2	0
Fuji	166	123	12	4	0	7	35	4	1	0	0	0
OKI	182	113	4	2	0	17	1	0	0	0	0	0
NTT	216	16	0	1	0	7	1	2	1	0	0	0
Showa	199	57	80	17	1	1	3	12	0	0	0	0
IBM	77	191	17	14	5	35	60	16	54	6	17	16

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Note: JP=Japan, US=United States, TW=Taiwan, CN=China, KR=Korea, EP=European Patent Office, GB=Great Britain, DE=Germany, FR=France, IB=International Bureau of the World Intellectual Property Office, CA=Canada, IT=Italy.
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For the top 10 companies in terms of all LED patents granted in all years, Table 8 shows the most common twelve patent authorities in which their applications were granted. The left column of the table lists the companies in order of number of patents received. The top of the table lists the patent authority under which an application was filed. Each patent authority is denoted by a two-letter code, listed at the end of the table. Numbers in the table indicate the number of patents granted to each company in each of the twelve leading patent authorities. For example, Samsung received 110 patents in Japan, 385 in the United States, 30 in Taiwan, 211 in China, 1,324 in Korea, 27 at the European Patent Office, 14 in Great Britain, 31 in Germany, 5 in France, none at the International Bureau of the World Intellectual Property Office, 1 in Canada, and none in Italy.

Inspection of the table quickly makes apparent that firms tended to file for patent rights in their home nations. There was a tendency to file for patent rights in the US, which has been the world's largest consuming economy, more often than in other nations. Nonetheless, apparently there were ample motivations for companies to file for rights elsewhere as well.

Some companies appear to file internationally less frequently than other companies. In the US, for example, GE and IBM contrasted in their filing strategies for LED-related patents. GE mainly defended its patent rights in the United States and Europe, while IBM obtained its patents somewhat more uniformly across nations, including in Japan.

4.3 Technology Sub-Domains

When analysis is focused on a particular technology sub-domain, the conclusions are somewhat different depending on the category considered. For the largest sub-domain (in terms of granted patents), Fundamentals, with 25,245 patents, Samsung had about three times the number of granted

patents, and almost four times the number of multi-national applications, as any other firm during application years 2004-2008. LG, Philips, Seiko, Siemens, Sharp, Matsushita, and Kodak had the next-highest rankings and were not enormously different from each other in terms of counts.

One of the key drivers of LED technologies in recent years has been displays. For patents related to displays, during the first half-decade (1999-2003), Seiko and SEL had the largest number of granted display patents. Sanyo, Philips and Sony followed with about 150 patents each and Sharp and Hitachi with just over 100 patents. Samsung and AU Optronics had similar counts, with Kodak and LG following closely. By the second half decade (2004-2008) Samsung had clearly broken away from the pack with nearly 1000 granted display patents. Seiko, LG, AU Optronics and SEL were far behind with only a few hundred granted patents.

Many analysts of the LED industry are interested primarily in lighting applications, for general illumination as well as for lights in vehicles and other applications. To analyze this range of applications, all patents were used except those related to displays, printers, and scanners. In this technology sub-domain, the top-ranked companies for 1999-2003 by patents granted were (in order) Siemens, Matsushita, Sharp, Philips, Toyoda Gosei, Nichia, Toshiba, and Sumitomo; or, using multi-national applications, Siemens, Philips, Toyoda Gosei, Sharp, Matsushita, Samsung, Sony, and Kodak. In 2004-2008, the top-ranked companies by (the limited number of) patents granted to date were Samsung, LG, Philips, Siemens, Matsushita, Showa, Seoul Optoelectronics, Seoul Semiconductor, 3M, and Seiko; or, using multi-national applications, Samsung, Philips, Siemens, LG, Seiko, Sharp, SEL, and Toshiba. American firms Cree, Kodak, GE, Avago Technologies, Agilent, and 3M were farther down the list among the leading companies, when ranked by multi-national applications in 2004-2008.

Focusing on a very narrow Lighting sub-domain, defined earlier to have a somewhat applied lighting focus, the big traditional lighting firms, Philips, Siemens, and GE, apparently had leading roles particularly during 1999-2003 and still somewhat during 2004-2008. Samsung and LG made important inroads into this category during 2002-2008. Four major players, Philips, Osram-Siemens, General Electric, and Matsushita, are thought to control about 70 percent of the global market and new entrants such as Sharp and Samsung, ushered in by their expertise in SSL, are poised to enter the lighting market.

OLEDs are an emerging technology that has been applied commercially to small displays and recently to televisions. For patents related to OLEDs, Samsung dominated in terms of the number of patents granted so far from applications filed in 2004-2008, with LG, AU Optronics, and Kodak being the distant followers. AU Optronics ranked somewhat lower (seventh) when multi-nation applications are used as the measure.

For patents or applications related to vehicles, the numbers of patents and applications involved have been much lower and it would be premature to try to rate the leading firms. Some of the leaders appear to be Koito Manufacturing, Siemens, Denso, Hella, Valeo, and Toyoda Gosei.

5. LEADING NATIONS

The nations in which strong LED-related R&D is occurring might be considered in two alternative ways: by company headquarters nation or by the nation in which invention occurs (specifically, the

nation of residence of each inventor circa the date of filing). The results are similar either way, and the focus here is on the nation of invention.

Figure 4 shows counts by time period for granted patents filed in 1999-2003 and in 2004-2008. The traditional dominance of Japan as an early developer of LEDs is apparent in both periods. However, the effect of Samsung's recent activity is apparent in the rapid growth of Korean patent counts in the latter period. The counts for Taiwan and China are higher than one might have guessed based on companies' activity, because large numbers of independent inventors and small firms have been filing for patent rights in both nations. Moreover, in both nations firms and individuals have been filing for large numbers of utility models, which are not considered in the counts of granted patents. This apparently reflects the manufacturing orientation of activity in the two nations, especially China. Similar patterns to those in Figure 4 are apparent when applications or multi-nation applications are considered. These metrics, however, suggest a substantially greater lead by Japanese inventors, with almost twice as many applications as those filed by Korean inventors even during 2004-2008, reflecting the large number of Japanese firms that have been active in LED research over the past decade.

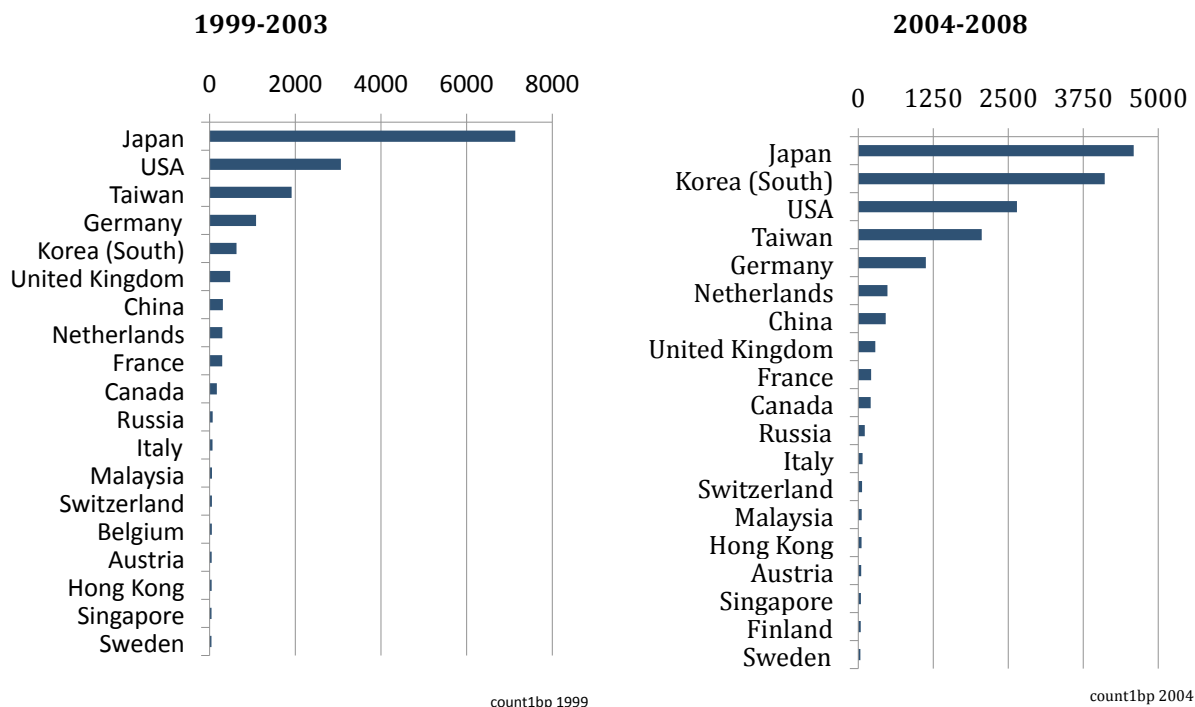


Figure 4. All LED patents granted in 1999-2003 and 2004-2008, by nation of invention (Copyright ©2009 Kenneth L. Simons, reproduced by permission)

Table 9. US applicants with greatest number of applications

Firm	HQ	Apps. All	Grants All	Patents						
				All	Except	Light.	Fund.	Displ.	Organ.	Veh.
Kodak	US	656.5	435.7	435.7	207.8	20.9	315.7	184.9	263.4	0.0
GE	US	374.0	318.0	305.8	258.7	114.7	161.1	43.7	30.7	0.6
IBM	US	233.7	204.2	204.2	125.2	12.1	163.9	77.5	27.5	1.0
Motorola	US	217.5	192.7	192.7	92.6	7.7	146.5	97.1	37.0	0.0
Westinghouse	US	209.4	191.0	191.0	143.4	118.4	37.7	41.6	1.3	2.6
Agilent	US	180.4	92.3	92.3	60.6	3.5	79.3	28.9	11.8	1.5
HP	US	174.2	125.3	124.1	70.1	3.6	82.7	35.7	5.5	0.0
3M	US	173.9	157.0	157.0	109.3	17.7	127.6	24.9	28.7	2.0
Cree	US	147.5	100.1	90.1	80.8	5.1	80.5	8.6	0.8	0.0

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Table 9 lists US companies with the greatest numbers of applications to date in the data, along with their numbers of applications, granted patents and utility models, and granted patents overall and by technology sub-domain. The list includes both presently and previously active firms, and provides a brief overview of a few of the key US players. While US firms have been less active in the past than their Japanese counterparts who rode the wave of successive applications of LEDs from watches to LED-backlit televisions, new firms like Cree and Color Kinetics (now Philips Color Kinetics) are pioneering architectural and general illumination lighting. It remains to be seen which firms will dominate in the emerging market for general illumination, and there is much competition with many strong contenders for market leadership.

6. CONCLUSIONS

The findings suggest a stronger role of organizations and individuals outside the US than has been apparent from previous studies of US patent data. More importantly, the evidence on patents and applications in nations outside the US provides a valuable opportunity to understand ongoing activity in SSL and LED R&D, helping to identify organizations with high R&D activity, emerging trends, and the tendency of some nations to focus on particular kinds of research or particular kinds of intellectual property rights.

Samsung was the company with the most rapid growth in application and patenting activity, and from 1999-2003 to 2004-2008 exhibited a several-fold increase in LED-related patents and applications. Samsung now has the most applications, patents granted, and patents granted rights in multiple nations (the latter a possible indicator of higher-quality patents). According to our analysis, Samsung had the highest counts in fundamental technologies related to LEDs and their use, in solid-state display technologies, and in OLED technologies, and the first or second highest count (depending on the measure used) in narrowly-defined lighting-specific LED technologies. In contrast, vehicle uses are one technology area in which Samsung is apparently a minor player. The data likewise show the technological positions of other leading companies across the globe, with tables providing convenient means to examine firms by technology area or nation, and for each of the alternative measures. Within US firms, Kodak, GE, Cree, and Agilent had the highest counts (depending on the measure used) among all LED patents from 2004 onward.

Geographically, we examined the locus of SSL and LED R&D in terms of specific nations. Nations where activity is prevalent were considered in terms of the headquarters locations of patent applications and in terms of the residence locations of inventors, but it turns out to make little difference which measure is used. Among all LED-related patents applied for in 2004-2008, the leading nations of invention in order were Japan, Korea, the US, Taiwan, Germany, the Netherlands, and China.

The leadership of Japan is hardly surprising given that nation's emphasis on the development of LEDs since the 1980s. Korea, Germany, and the Netherlands each have strong roles for specific companies, Samsung, Siemens, and Philips respectively. Activity in Japan, the US, Taiwan, and China has in contrast been spread across much greater numbers of companies. The Taiwanese industry remains a powerhouse in semiconductor manufacturing, and corporate and national policies have been extending this dominance to LED manufacturing. A burgeoning Chinese industry is also contributing to manufacturing, spurred in part by the creation of manufacturing sites across the Taiwan Strait from Taiwanese companies, and a large number of short-term utility models have been filed by and granted to diverse companies and individuals in China.

The data also reveal where leading companies have been filing their LED-related applications, confirming the tendency of companies to file in their home nations. This evidence provides interesting insight into how companies have been balancing the need to obtain international rights with the costs of filing in multiple nations. Companies like Samsung, Sharp, Matsushita, Philips, and Siemens routinely obtain patents in disparate regions around the globe, whereas other companies including GE appear to have developed patent portfolios that tend to be constrained to specific nations.

The data provide stimulating evidence on SSL and LED R&D activity and on the use of patents worldwide. While some of the evidence confirms patterns already well known to industry insiders, the ample data compiled here can help with strategic business decisions and help government policy makers better understand the current state of patenting in LED-related technologies. While this paper provides important insights into global patenting, it suggests important new questions that should be addressed in future research. Why have some companies expanded or closed their LED-related activities? What has led companies from one area of technology to another and what similar patterns may follow in future, as for companies moving from LED displays into LED lighting as well? What factors drive applicants' decisions to file in their home nations or in other locations? In addition, the study raises issues about levels of competition in R&D and the extent to which certain firms dominate specific technology arenas, potentially limiting entry options for possible competitors. Further study could also be directed toward a better understanding of when and why companies license technologies to each other and what impact those decisions have on competition.

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