MAGIC Technology - WHITE PAPER

Scene contrast indexed image sensing with WDR

Abstract

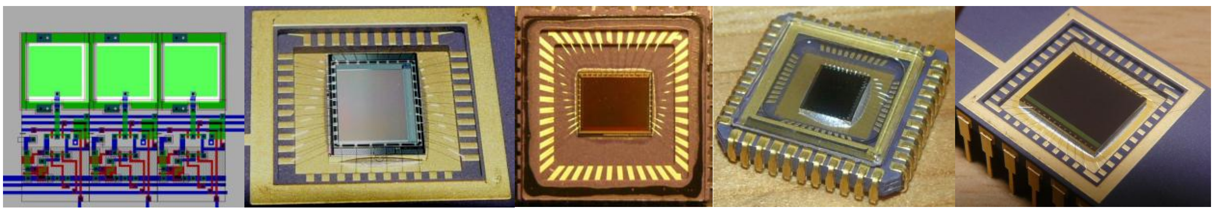
This paper addresses a new generation CMOS imaging technology named MAGIC (**M**atrice **A**ctive à **G**énération d'**I**mage indexée sur **C**ontraste). This technology is capable to generate a high quality contrast indexed image under very wide intra scene dynamic range (> 120dB) in a single shoot.

The concept of MAGIC imaging technology includes a new pixel design based on logarithmic photo-voltaic operation mode photodiode and associated video signal processing method generating a contrast indexed output image with pleasant visual appearance and invariance to average scene illumination level.

This new imaging technology gives the following advantages:

- High quality output image, ultra low Fixed Pattern Noise (FPN), high sensitivity and no image lag, etc.
- Contrast indexed image for easier and better scene analysis
- Fully encapsulated imaging module, ideal for System-on-Chip integration
- Free of hot or flickering pixels
- High manufacturing yield for large size array
- Simple and compact pixel design in standard CMOS process

MAGIC technology has been approved in two different CMOS process (0.35um) from two European CMOS foundries. The validation in 0.18um CMOS technology node is on the way. The MAGIC sensing technology has been developed by research team in Institut Telecom Sud Paris, lead by Professor Yang Ni, since 1994 and protected by several issued and pending patents.



1994 **2000** **2005** **2006** **2008**

Introduction

Imaging devices transform a 2D optical image into an electronic signal. This video signal can be used for both human remote observation and automatic machine vision. The imaging quality and performance are determinant factors for the global performance of such vision system.

An imaging device performance can be characterized by a metric of 3 dimensions:

- Spatial resolution – how fine is the 2D optical image sampled
- Signal quality – how clean is the video signal
- Operation dynamic range – how large the light variation can be tolerated.

An imaging technology includes two basic techniques:

- photoelectric conversion in each image point (pixel)
- arrangement and access mechanism to pixels in a 2D array.

For virtually all the commercialized solid state imaging technologies, the photo electrical conversion is based on the accumulation of photo electrons (or holes) during a pre-determined duration called exposure time. As shown in Fig. 1, this principle is used both by CCD and by classic CMOS imaging technologies in VIS-NIR spectral band.

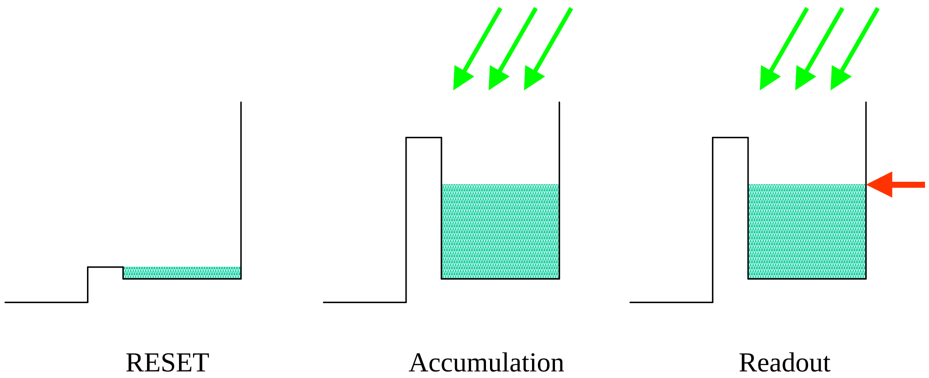


Figure 1. Function cycle of a photodiode: reset, accumulation and readout.

CCD and CMOS technologies differ at the access mechanism to pixels in a 2D pixel array. CCD uses analog charge mode shift register to shift sequentially all the pixels one by one from the 2D imaging array, but CMOS uses circuit-switching based access direct to pixels in a 2D imaging array. This is illustrated in Fig. 2.

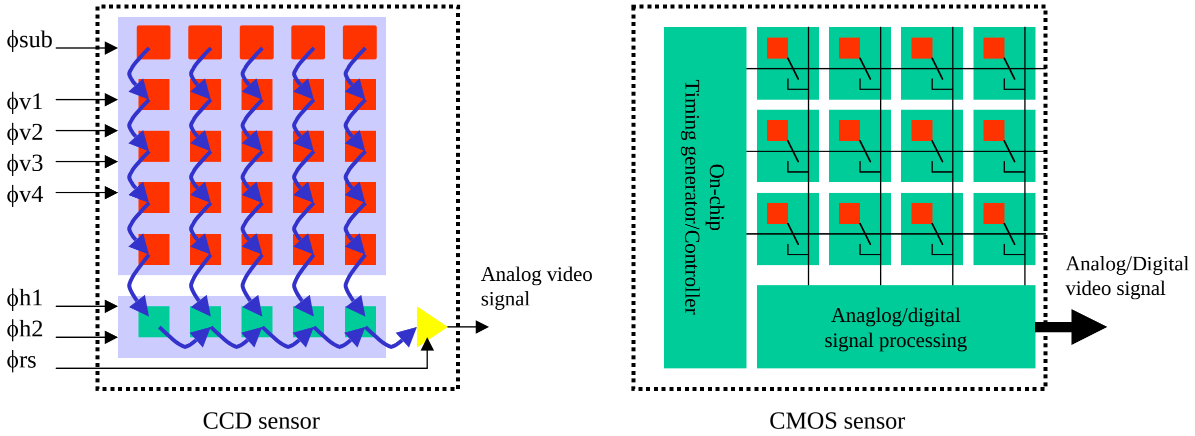


Figure 2. Conceptual structure of CCD and CMOS imaging device.

A potential advantage of CMOS imaging technology compared to CCD one is its possibility to integrate on-chip image processing on the same imaging device, either as an independent part or as an incorporation inside each pixel[1]. The optical mouse sensor is a typical example. But all this potential advantage is of course conditioned by the image sensing performance of the basic CMOS imaging array.

With the huge progress in integration technology, the resolution of imaging devices has been improved considerably during the last decade. It is very common today to find multi-million pixel sensors in very cheap consumer cameras. The video signal quality is also improved, but in a less degree. It can be attributed mainly to digital image processing techniques and noise reduction techniques. But the dynamic range remains quite unchanged or slightly degraded due to smaller pixel size during the last decade. Even the most sophisticated DSRL cameras show no more than 8 EV (1:256) useful dynamic range[2]. This relatively low dynamic range limits seriously the imaging performance in two situations:

- Highly differently illuminated scene (local saturation)
- Fast illumination changes (local or total saturation due to sensor control delay)

These two situations are omnipresent in many existing and emerging applications such as video surveillance, helmet camera, automotive vision, industrial process monitoring, etc. MAGIC imaging technology is invented to resolve the low dynamic range limitation of current solid state imaging technologies and improve spatial resolution and signal quality at the same time.

Dynamic Range, Contrast and MAGIC imaging principle

It’s should noted that the common definition of sensor’s dynamic range is the ratio between its maximal signal amplitude and its noise floor. The typical value is about 50-60dB for commercial CMOS/CCD sensors, which seems large enough. But in reality, the tolerable illumination variation range is much lower than this. For reproducing sufficient grayscale details, at least 100 nuances are needed. Suppose that each nuance step be set at the noise floor amplitude, this will take 40dB of a sensor’s dynamic range and leave only a margin of 10-20dB for accommodating the scene illumination disparity, which is very often not sufficient as shown in Fig. 3.

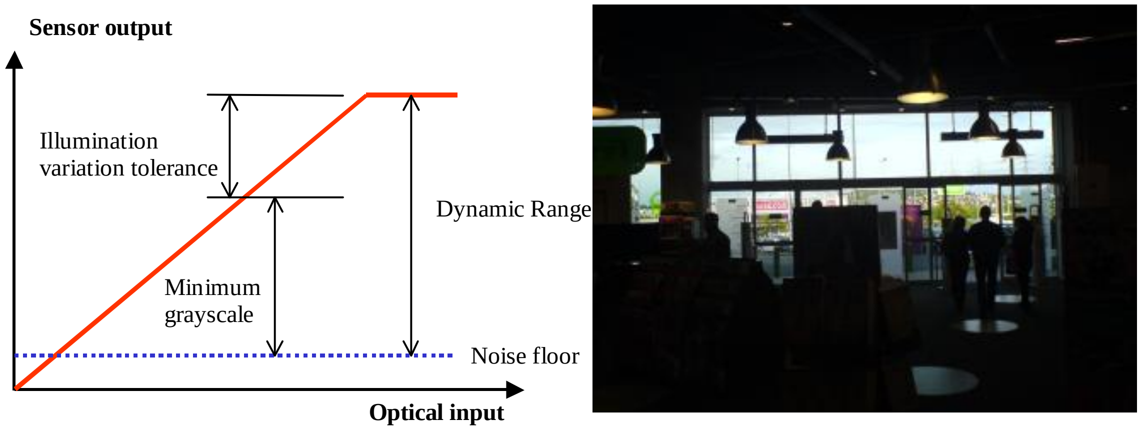


Figure 3. The illumination variation tolerated by a classic sensor is much lower than its announced dynamic range.

In the visible and near-infrared (VIS-NIR) spectral band, the optical image of a scene is formed from the reflection of light sources by the visible surface of objects in the scene. The reflectance (the reflected percentage of incident illumination) of a visible surface varies typically from 1% to 100%. As shown in Fig. 4, the whitest and darkest patches on the testing chart represent a reflectance of 89% and 3.2%. So this means that the dynamic range of the reflectance in a scene is very limited, say 20-30dB only, but as shown in Fig. 4, the luminance ratio in a common office scene reaches 84dB !

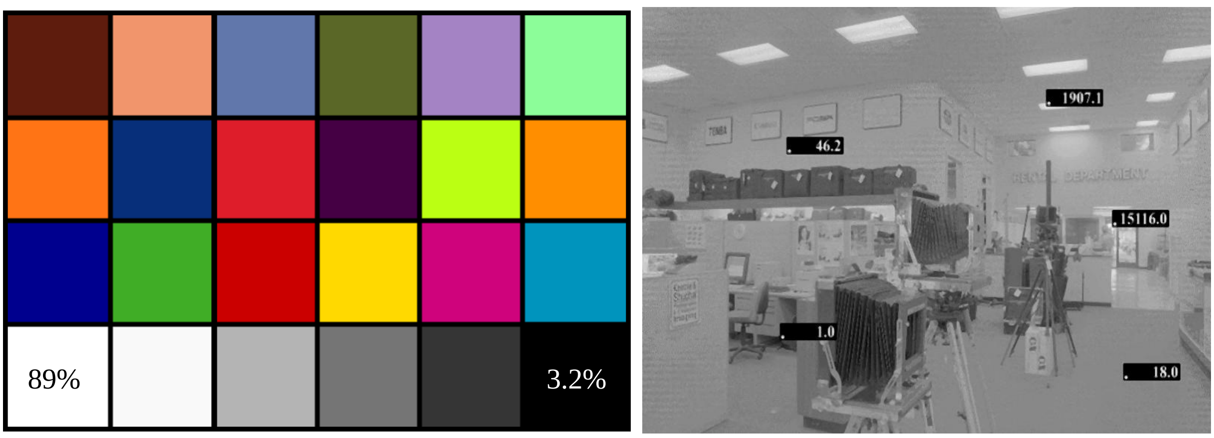


Figure 4. The whitest square and the darkest square on the bottom of this chart represent a reflectance value of 89% and 3.2%. This represents almost the largest contrast of everyday objects. The large dynamic range in a scene is created by the illumination distribution in the scene (measured in relative luminance).

This is not the case for illuminating light sources and the illumination level distribution in a scene. The illumination difference can easily exceed 120dB in many everyday situations. Fig. 5 shows a video capture from a traffic surveillance camera. The Sun set causes a large illumination level difference on the highway. The CCD camera can not handle such dynamic range and generate by consequent a large local saturated region on the image where no detail can be distinguished at all.

Figure 5. A typical traffic surveillance video recorded image. The huge intra scene dynamic range is created by the Sunset, but not by the objects in the scene.

The illumination light is only an information vehicle which does not carry much information on the observed scene. But a classic imaging technology has to cope with this huge dynamic range in order to conserve a low dynamic range visual information, this is surely not a smart way to follow. A clever method should use a sensing technique which can separate the illumination component and the reflectance component of a scene. A logarithmic transfer function permits this separation:

$$\log\vec{S}=\log\vec{L}+\log\vec{R} \qquad (1)$$

where $\vec{L}$ and $\vec{R}$ represent the illumination distribution and the reflectance distribution of the projected 2D image of a scene.

With a logarithmic transfer function in photoreceptor, the illumination component is separated from the reflectance component. In most of cases, the illumination on a scene is quite smooth and manifests as a global offset on the output image. By using an adequate image pre-processing, we can normalize this illumination related offset to a pre-defined level:

$$I_{magic}=\log\vec{S}_{normalized}=\log L_o+\log\vec{R} \qquad (2)$$

This operation is equivalent to normalize the scene illumination level, L_o . In this way, a scene under different illumination levels will be perceived as the same. This is what happens in a human eye. The prove is that even the most expert photograph has to use a photometer to measure the illumination level before photo shooting because the real illumination information is removed by eyes and brain. MAGIC imaging technology is based on the same principle. That is why MAGIC technology based camera can give a very natural scene image as we saw it. Fig. 6 gives a video capture of a MAGIC camera chip of a highly contrast scene. It can be noted that the details in the dim regions inside the cabinet, under the shadow can be perceived as well as those in the very bright Sun shined regions.

Figure 6. A sample image from a MAGIC camera chip of a scene with huge intra scene dynamic range. The MAGIC camera chip produces a very pleasant image conserving the visual detail over the whole scene in this extreme lighting conidtions.

Technology background of MAGIC

The logarithmic law image sensing is not new. The first tentative with an experimental implementation in CCD technology has been done by S. Chamberlain, founder of DALSA, in 1984[3]. Following on the same principle, several other explorations in CMOS technology have been undertaken by different research and industry teams[4][5][6][7][8]. The main problems in these CMOS logarithmic photoreceptors are:

- Huge FPN noise (larger than useful signal)
- Low sensitivity
- Difficult FPN compensation
- Distortion of logarithmic response
- Sever image lag in dim conditions

The most common CMOS logarithmic photoreceptor design is shown in Fig. 7. In this configuration, the linear photo current passes through a sub threshold operating MOS transistor. The exponential characteristic between the gate-source voltage and the drain current transforms the linear photo current into a logarithmic-like voltage output signal.

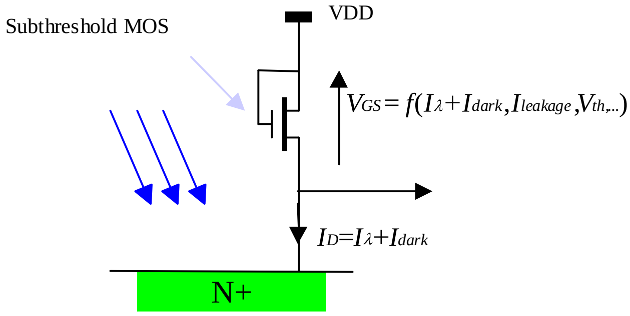


Figure 7. Classic CMOS logarithmic-like response photoreceptor which uses a sub threshold mode MOS transistor to convert linear photo current in the photodiode into a logarithmic-like voltage output.

The FPN noise in this kind of photoreceptor has its origin from 3 different sources:

- MOS threshold voltage dispersion
- Photodiode dark current and its dispersion at low light conditions
- MOS operating mode transition dispersion at strong light conditions

All these FPN sources and phenomena are mixed together in a highly non-linear device, so it is virtually impossible to create a simple FPN compensation on the whole operating dynamic range of such “wide dynamic range” photoreceptor.

MAGIC imaging technology uses a revolutionary new pixel design based on solar cell mode photodiode in which the image signal is formed by the open-circuit voltage of a photodiode under illumination[9]. In a photo voltaic mode, the open-circuit voltage is proportional to logarithm of the incident light intensity on a very large dynamic range. This principle can be used not only in a silicon based photodiode but also in any PN junction based photodiode such as InGaAs, InSb or HgCdTe in NIR-MWIR-LWIR band for example.

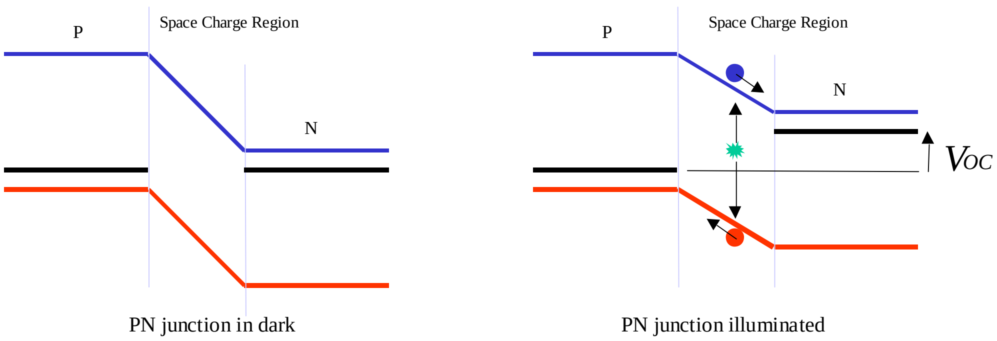


Figure 8. Under illumination, an open-circuit PN junction will generate a potential difference which is proportional to the logarithm of the illumination intensity on a large dynamic range.

This principle is shown in Fig. 8. In an open-circuit PN junction, the light induced electrons-holes are separated by the built-in electric field in its space charge region. The separated negative (electrons) and positive (holes) charge generate a potential difference which is proportional the logarithm of the electrons-holes concentration which is in turn linearly proportional to incident photon intensity. The open-circuit voltage can be expressed by the Schokley equation over a very large dynamic range of photon flux intensity:

$$V_D=\frac{kT}{q}\ln\left(\frac{I_\lambda+I_s}{I_s}\right) \qquad (3)$$

In this photo voltaic operation mode, two key characteristics should be highlighted:

- the electric field in the space charge region is low and limited to its built-in value;
- the image signal generation involves mainly the majority carriers.

The defects and contamination in PN junction have strong influence on the minority carriers related behaviors but only have marginal impact on majority carrier based behaviors. This means that the MAGIC pixel can be very uniform, stable even at high temperature and also of high manufacturing yield. These characteristics have been verified on the working silicon chips from different CMOS foundries. Fig. 9 shows the measured output voltage from 3 pixels on an experimental CMOS circuit. The useful dynamic range exceeds 120dB. Please note that the starting point of the illumination level corresponds approximately 3mLux, the prove of high sensitivity

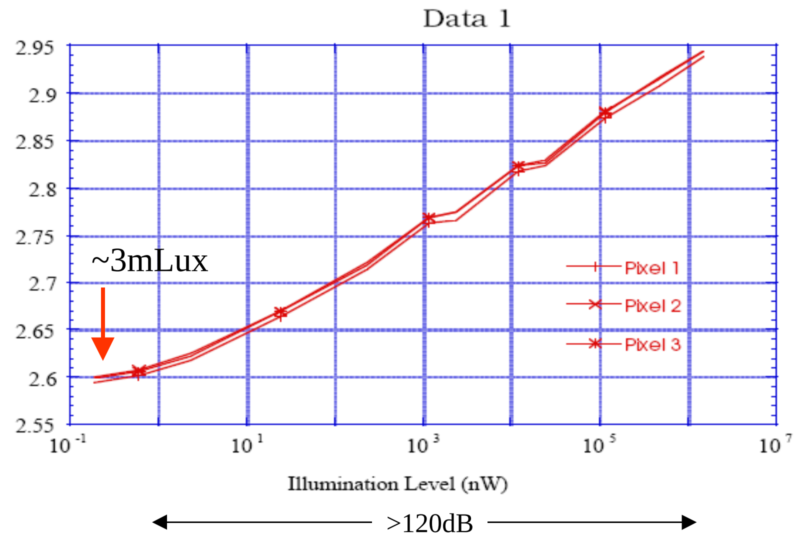


Figure 9. The measured output voltage of 3 pixels on an experimental CMOS chip. The illumination (3000K°) level was measured by using a radiometer with 5mm diameter silicon photodiode probe.

With NIT's skilled design, the total output random noise is under 300µV equivalent at the photodiode and the FPN can not be measured on the output image. This noise performance gives a maximal contrast sensitivity around 1%, similar to the performance of human eye under its optimal viewing conditions. The response curve matches perfectly logarithmic law as shown in Fig. 11(extracted from [10]). The low light sensitivity is good, our working sample sensor can capture useful quality image under sub-Lux illumination condition at 50 images per second with F1.4 lens.

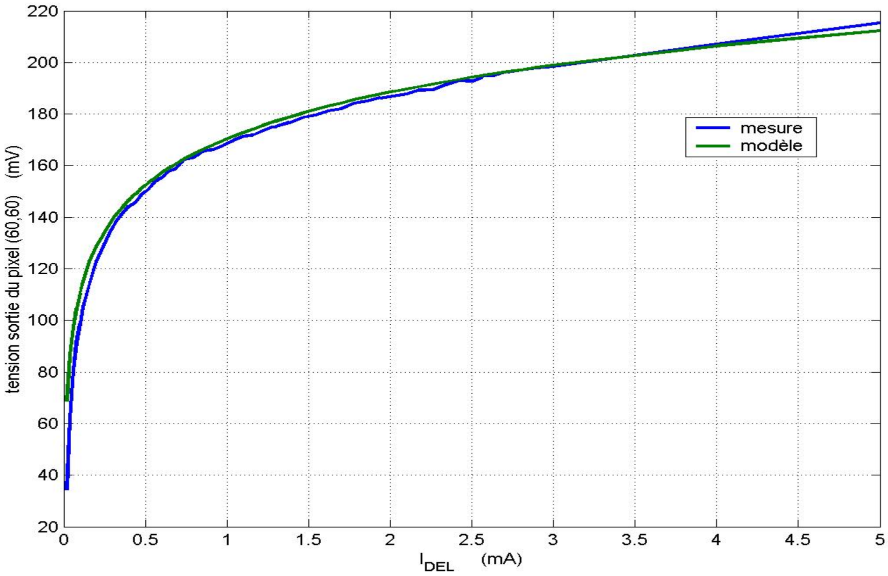


Figure 11. The measured photoelectric response curve from a 160x120-pixel prototype sensor. This sensor has been designed and fabricated in AMS 0.8um CMOS technology. The illumination is created by a LED with an optical output power highly linear with the driving current.

MAGIC video signal processing

Until now most of imaging devices are involved in remote observation applications. The output video signal should give a pleasant and easy to interpret visual aspect on the classic display device. It is well known that the image reproduction for human vision has to respect the following law:

$$\frac{dI_{display}}{I_{display}} = \gamma \frac{dI_{scene}}{I_{scene}}, \text{ where the } \gamma \text{ plays a contrast modulation role.} \quad (5)$$

This shows that the absolute luminance intensity has no influence on the fidelity of the image reproduction. This property gives a lot of design freedom in imagingsystem designs. Most of commercially available video cameras respect this law and give quite natural image for human eye when they are operating inside its dynamic range.

It's clear that a native logarithmic response doesn't respect this law, the raw output image, when displayed on classic monitor, will give a unnatural visual appearance. But fortunately, in a pre-determined interval corresponding to the most often contrast ratio in a natural scene, a logarithmic function can be very well approximated by a square root function. Fig. 12 gives a plot of squared logarithm function in the 1 to 10 interval.

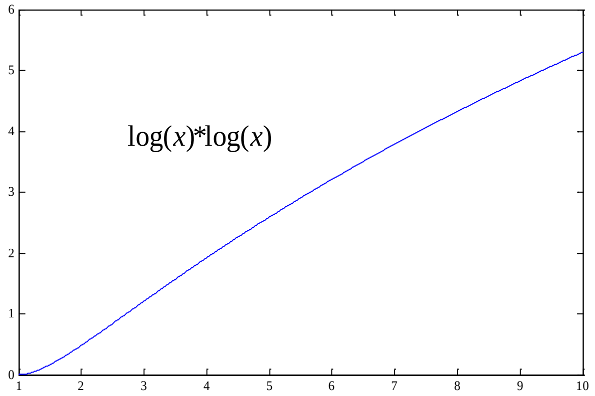


Figure 12. In the low value interval, a logarithm function can be approximated by a squared function.

In this interval, the logarithmic function is very close to a square root one which respects the equation (5). MAGIC imaging technology uses proprietary on-chip video signal processing to place the raw logarithmic video signal into an adequate square-root-law-like region. In this case, the output video image will be equivalent to a gamma = 0.5 video signal, perfect to be displayed on any traditional TV monitors. Fig. 13 gives an example of scenes captured by MAGIC camera chip, the images are perfectly pleasant to human observation. This principle is very similar to the image orthicon tube where the response is logarithmic inside its very limited dynamic range[11]. It produces images particularly pleasant to human eyes as can be seen in a lot of video clips of Beatles.

Figure 13. By placing the logarithmic image in an adequate interval, a very pleasant $\gamma = 0.5$ image can be obtained. The images have been captured from a 352x288 MAGIC camera chip designed and fabricated in AMS 0.35um CMOS. Please note that the images are coded only in 7-bit despite of the large dynamic range of the scene due to the presence of specular reflections.

The output video signal of MAGIC camera is contrast indexed. The following equation connects the absolute luminance of the scene I_{luma} and the contrast indexed signal I_{magic} from MAGIC sensor :

$$I_{luma} = L_o C_o^{I_{magic}} \qquad (6)$$

where L_o represents the preset illumination level and C_o represents the contrast sensitivity of a MAGIC sensor.

This means that by using an off-sensor digital processing unit, the output image of MAGIC camera can be re-translated into linear mode luminance image. This transformation gives the possibility to simulate all the exposure setting related phenomena in a conventional linear law camera. Fig. 14 gives an example: from just one MAGIC image, an equivalent linear mode image with different camera setting can be obtained.

This example shows that with virtually all the luminance distribution information of a scene can be conserved in a single MAGIC capture. From this MAGIC image, different exposure effects can generated by a digital image processing. This property is extremely interesting for shooting fast going events where there is no time to set an adequate exposure value.

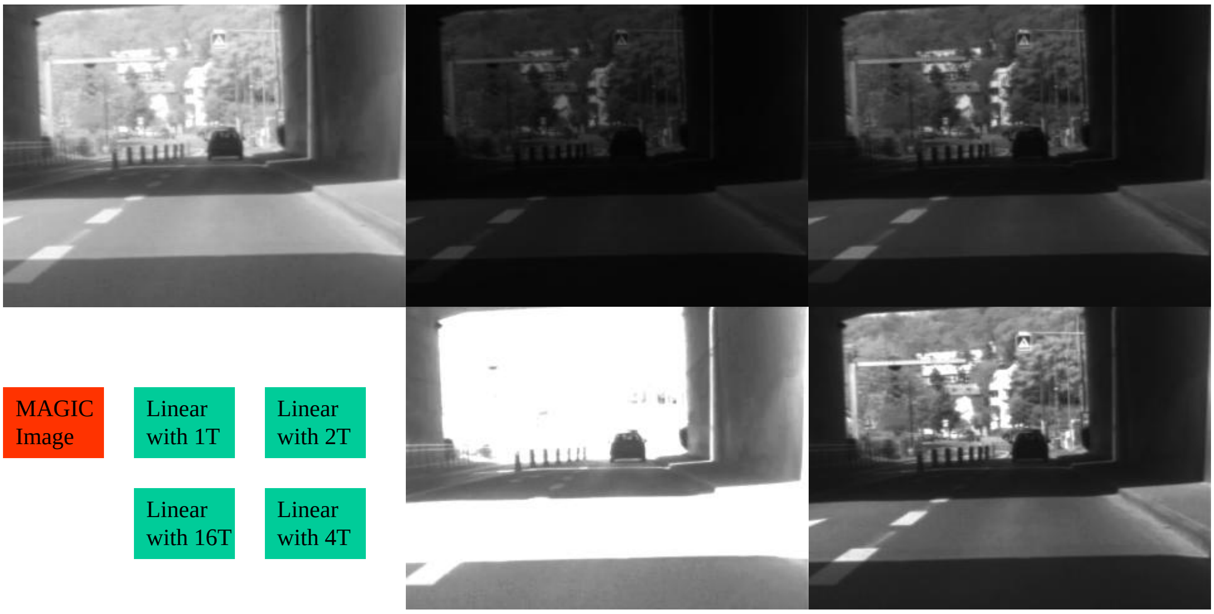


Figure 14. The wide dynamic range linear luminance image can be re-synthesized from a single MAGIC image. This linear image can be "re-photographed" by a virtual linear camera with different virtual exposure times to highlight different regions. The original image is extracted from a video recording of MAGIC camera module mounted on a car.

Advantages of MAGIC imaging technology for

Application Specific Imaging Devices

In many embedded applications such as smart surveillance camera, automotive vision sensors, etc. the hardware complexity, processing capability and power consumption are limited. Specially designed application specific imaging device can incorporate very efficient on-sensor-chip image pre-processing optimized for the target application and also for the post-digital processing unit. A better, cheaper and cooler solution can be obtained. MAGIC imaging technology can isolate the image sensing portion completely from the image processing portion and result in faster, easier and more reliable development with short time to market and low development cost and risk.

Recognition and scene analysis oriented applications

Recognition and scene analysis play a more and more important role in automatic video surveillance applications. Most of the recognition and scene analysis are based on the visual surface reflectance map extraction which is relatively insensitive to ambient light changes. This extraction is time-consuming on DSP based platform. MAGIC camera chip can output virtually directly this reflectance map without additional computation. The example applications are face recognition, especially under out-door conditions, artificial vision based perimetric surveillance, critical situation/event warning in public spaces.

Automotive vision

Automotive vision covers a large field of image sensing, processing, transmission and display aspects. But the common limitation resides in the image sensing stage because of large scene dynamic range and fast illumination changes on the road. MAGIC imaging devices capture reliably image under these challenging conditions. Besides the contrast indexed output image can facilitate most of the image analysis necessary in automotive vision. For example, the white traffic marks will keep a constant difference to the road surface whether in the Sun shine or in the shadow. Stereovision based 3D sensing can benefit a lot from MAGIC technology, because the stereo matching can be done by using mostly contrast related information which is closely attached to the visual objects themselves. The absence of local saturation will insure a complete 3D map without possible no-data regions caused by local saturation in a classic CCD/CMOS camera based implementation.

Intensified vision

Intensified vision is very useful for a lot of applications from well known defense/surveillance to scientific observation. The image intensifying devices such as image intensify tube can apply huge luminance gain, very often superior to 10000, on the scene image before it arrives on a solid state image sensor. Till now, the useful dynamic range of an intensified camera is limited by the solid state image sensor stage. MAGIC image sensor can overcome this technological barrier and extend considerably the global dynamic range of such intensified camera. The very large dynamic range of MAGIC sensor can not only increase the global intra-scene dynamic range but also keep the pixel size small for high image resolution. The dynamic range margin of MAGIC sensor permits to set the intensification gain at a much higher level and by consequent an important improvement of the absolute sensitivity.

Professional photography/video recording

Covering unexpected events is the paramount mission of newsmen. MAGIC imaging technology can be used in high quality CMOS sensor for professional photography/video camera which permits an exposure-free image shooting. The image can be post processed on computer to give virtual any exposure effects in order to highlight the different aspects of the covered event.

This is very interesting for common DVR connected CCTV cameras. As shown in Fig. 14, a MAGIC video stream even coded in standard video recording format can conserve virtually all the luminance details of a scene. By using simple image processing later, a large degree of details can be recovered for after-event inspection. This extended scene observation and recording capability can be done without any change to existing camera-DVR infra-structures.

Mobile phone camera

Mobile phone camera represents the biggest market for CMOS camera chips. More than 40% mobile handsets are equipped with CMOS camera chip. This percentage increases constantly from year to year. The mobile visiophone will be one of the killer applications for the newly introduced high speed 3G service. MAGIC camera chips can give a very pleasant and stable video image under the very challenging out-door mobile lighting conditions. This highly stable image will simplify the video processing and coding software and hardware, give a better video quality with lower global power consumption and hardware cost. The fully encapsulated MAGIC imaging module design can facilitate the camera interface design in order to cope with the rapid market tendency evolution.

Conclusion

This white paper gives a short summary of our innovative MAGIC imaging technology. This technology has been invented and developed since 1994 with a large scientific endeavor of all the team members working on this technology. The basic concept of this technology is simple despite of many technical implementation challenges in CMOS technology for obtaining crystal clean image.

We have demonstrated that with MAGIC technology, logarithmic law image sensing device can give equivalent or even better S/N ratio than a conventional CMOS active pixel sensor with very low FPN at the sensor's output. The virtually unlimited instantaneous dynamic range of MAGIC technology is an enabling technology not only opening the door to many long time dreamed human and machine vision based applications but also giving the possibility to improve greatly the performance of existing systems.

We will dedicate our effort to continue the improvement of MAGIC imaging technology and its portage to different mainstream CMOS technologies. We expect that our MAGIC imaging technology could be a helpful tool for the success of your system and application innovations.

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