Indirect X-ray imaging detector resolving 200 nm line-and-space patterns by using composite of transparent ceramics

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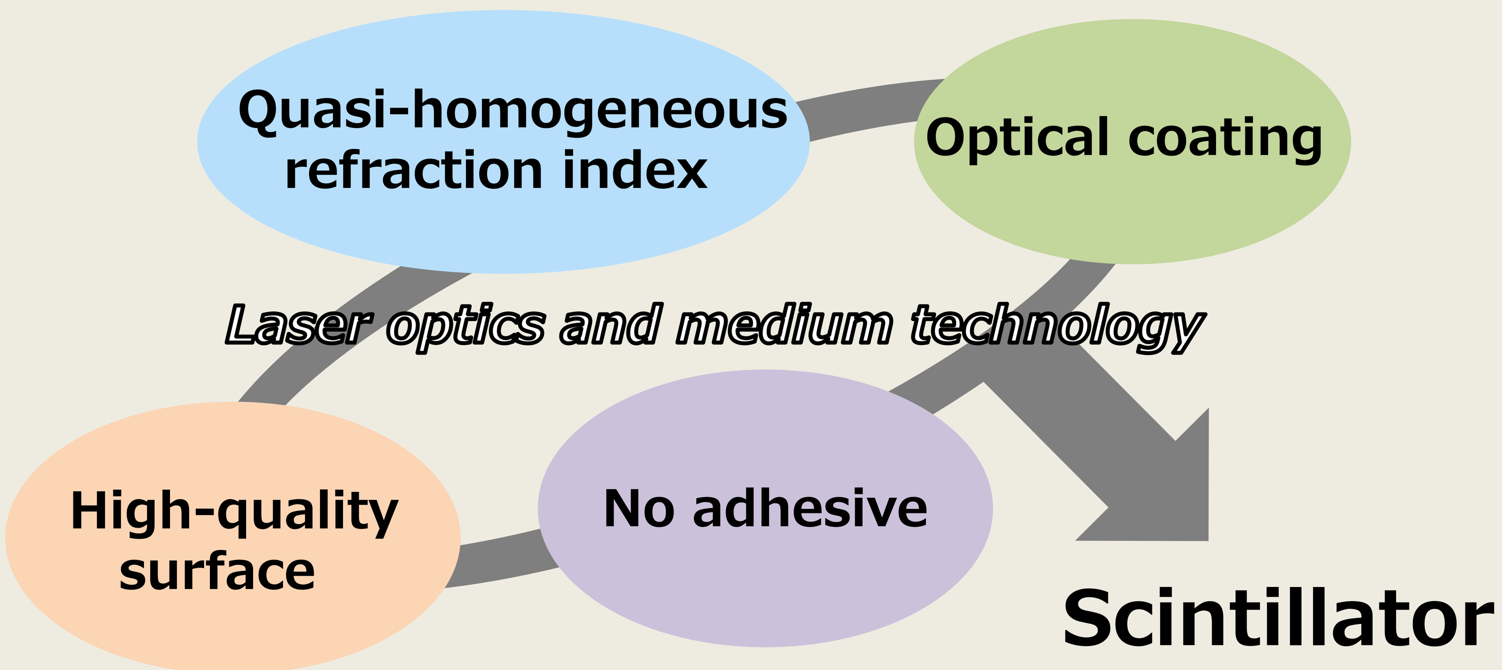
Abstract

A high-resolution lens-coupled X-ray imaging detector equipped with a thin-layer transparent ceramics scintillator has been developed. The scintillator consists of a 5 μm-thick Ce doped $Lu_3Al_5O_{12}$ layer (Ce:LuAG) bonded onto the support substrate of the non-doped LuAG ceramics by using a solid-state diffusion technique. The effective pixel size on scintillator plane was 65 nm. X-ray transmission images of 200 nm line-and-space patterns were successfully resolved. X-ray imaging of very large scale integration (VLSI) circuits was demonstrated and the wiring patterns in the inner layers were clearly visualized.

Introduction

We applied high power laser optics and medium technology [1,2] to a scintillator. This provides quasi-homogeneous refraction index structure, high-quality surface, direct bonding without adhesive layer, and optical coating.



- **Elimination of optical problems such as**
  - ✓ Defocus light
  - ✓ Light diffusion (multi-reflection, scattering)
  - ✓ Wave front aberration
- **Direct bonding**
  - ✓ provides radiation hardness because of no-adhesive layer
- **Radiation shield**
  - ✓ Millimeter-thick substrate attenuates X-ray to 10^{-43} order at 10 keV. This enables high NA lens with short working distance to be installed.

Fabrication process of a thin film scintillator

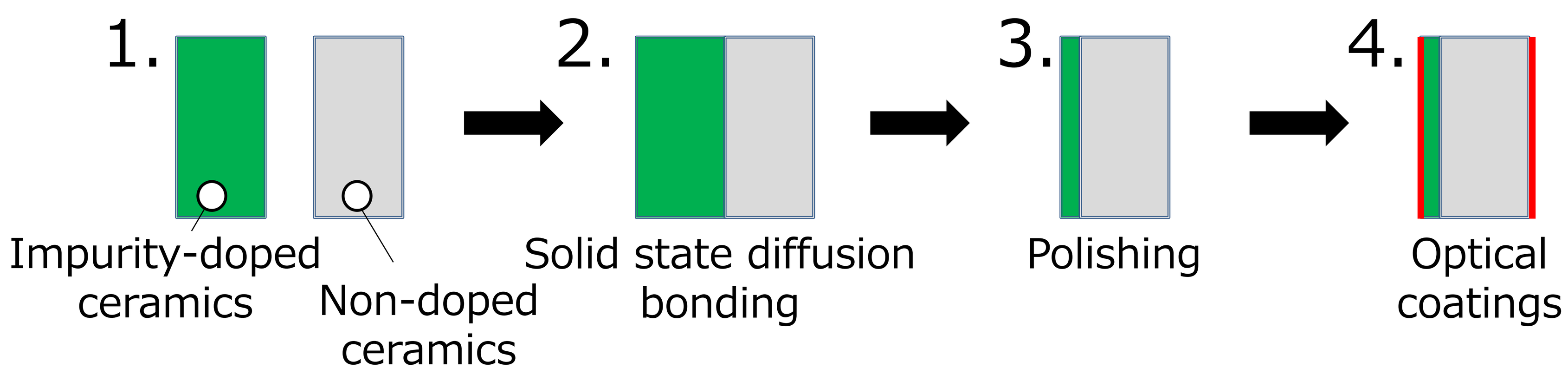
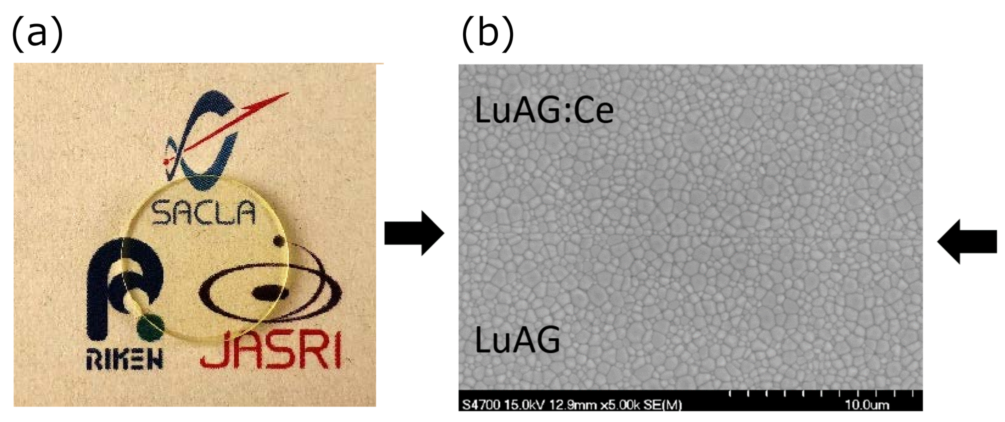


Fig. 1 Schematic of a thin-film scintillator layer fabrication [3]

1. A scintillator and a substrate are produced from identical material.
2. The composite of the impurity-doped ceramics (scintillator) and the non-doped ceramics (substrate) are formed by the solid-state-diffusion bonding method.
3. The scintillator layer is grinded, lapped and polished to be thinned down to ~ 5 μm.
4. The surface of non-doped ceramics is coated by an anti-reflection film. For the surface of impurity-doped ceramics, there are two options of anti-reflection or reflection films.

Produced scintillators



The scintillator thickness can be controlled in wide range scale of μm ~ mm order. The production of a large scintillator with an area of up to 100 mm is also available by using solid-state-diffusion bonding method. The transparent ceramics and solid-state-diffusion bonding technique are provided by Konoshima Chemical Co.,Ltd [1, 2].

Fig. 2 (a) Photograph of 5 um thick LuAG:Ce on 1 mm thick LuAG
(b) Secondary electron micrograph of bonded interface of LuAG:Ce and LuAG

Evaluation results

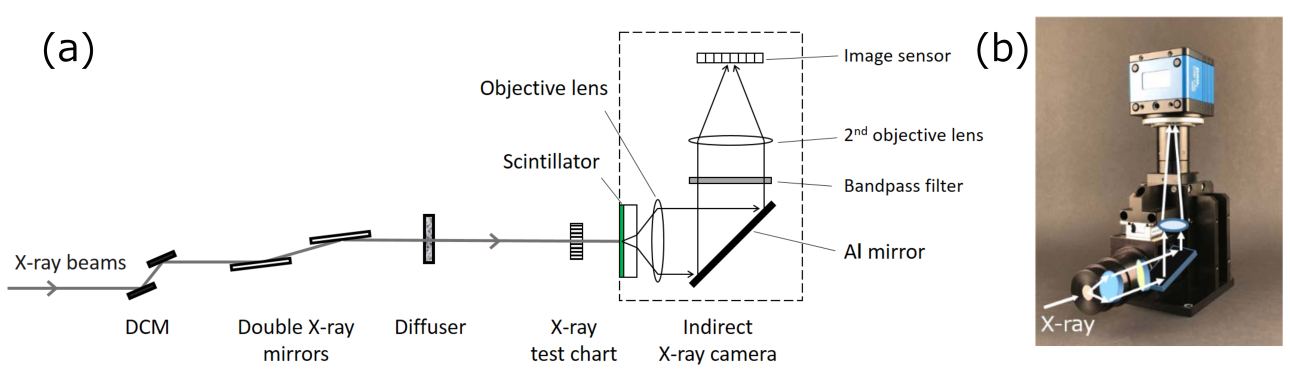
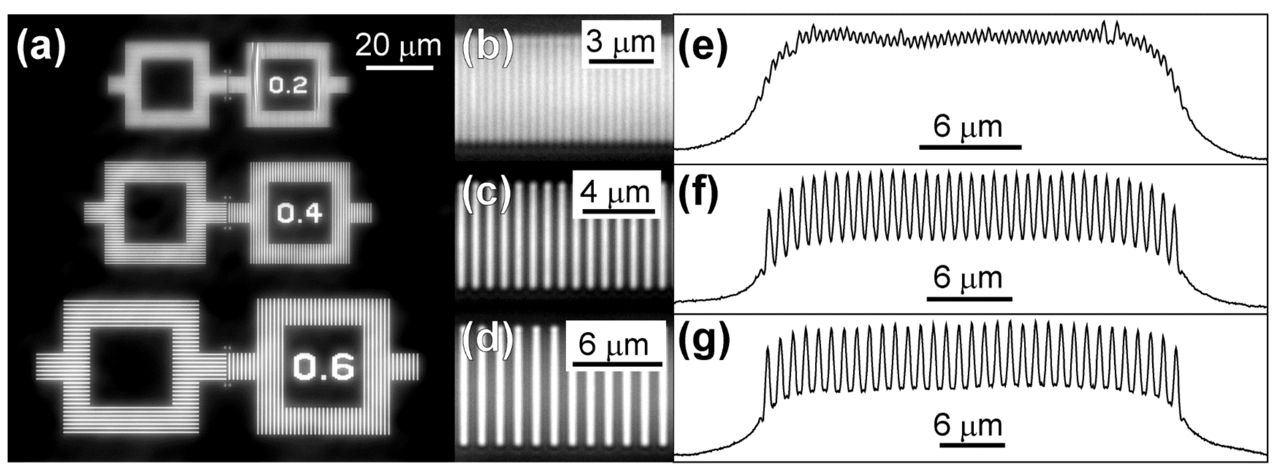


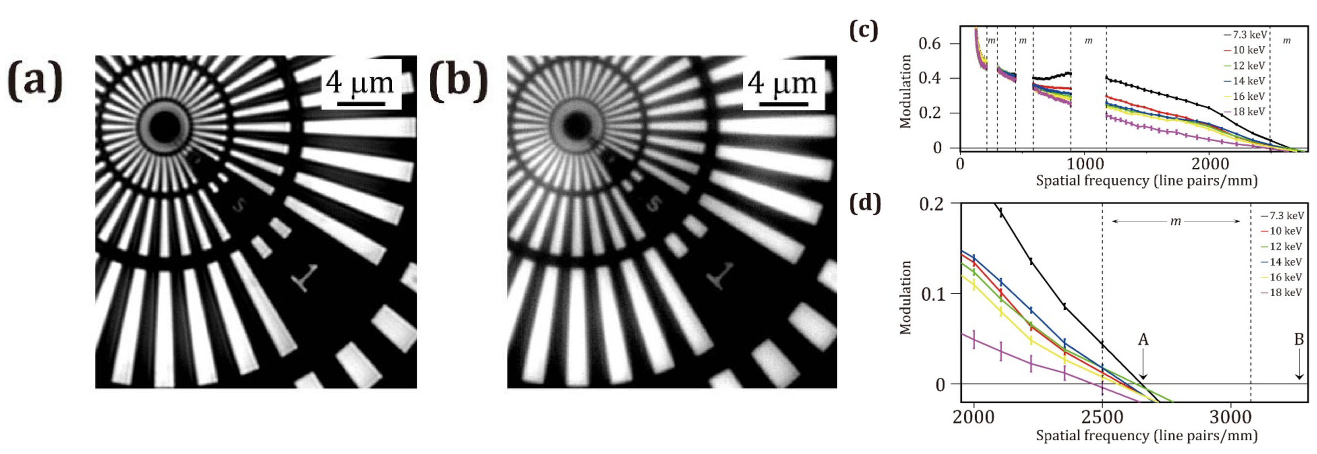
Fig. 3 (a) Experimental setup
(b) Photograph of X-ray imaging detector

- **SPring-8 BL29XU collimated X-ray beam (unity magnification)**
- **5 μm-thick Ce:LuAG (520 nm fluorescence)**
- **Numerical Aperture: 0.85**
- **Effective pixel size: 65 nm**
- **Working distance ~ 0.5 mm to minimize X-ray diffraction**



- **200 nm line-and-space was clearly resolved.**
- **The contrast of 400 nm and 600 nm patterns have achieved to nearly 50 %**

Fig. 4 (a) Microradiograph of tantalum line-and-space patterns at photon energy of 7.3 keV.
(b, c, d) Zoomed images at the area of 200, 400, and 600 nm line-and-space patterns, respectively.
(e, f, g) Projection profiles at the areas of 200, 400, 600 nm line-and-space patterns, respectively.

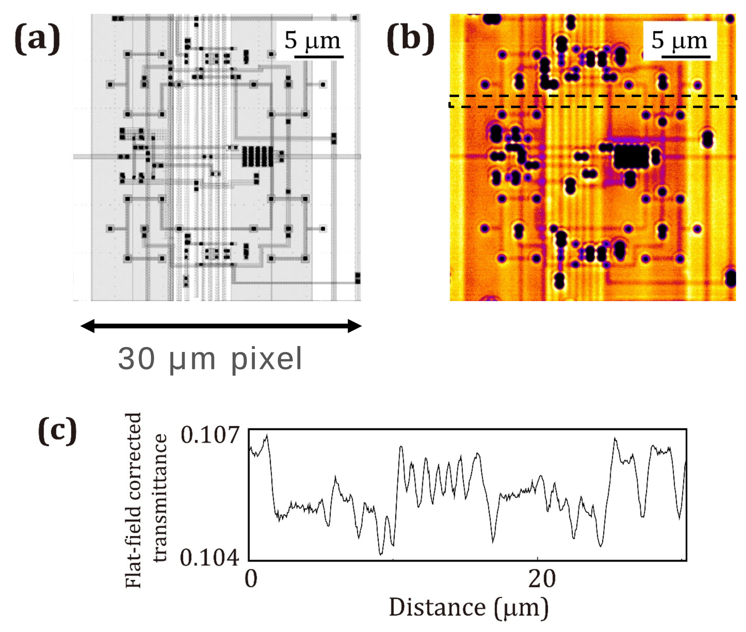


- **Cutoff frequencies have achieved 2500 lines/mm or higher at every photon energy of 7.3 ~ 18 keV**

Fig. 5 (a, b) X-ray transmission image of the Siemens pattern at 7.3, 16 keV. (c) Plot of modulation transfer function at photon energy of 7.3 ~ 18 keV. (d) zoom of (c) at cutoff frequency region

The detector has successfully resolved 200 nm line-and-space patterns. The diffraction limit for the fluorescence wavelength of 520 nm and NA= 0.85 gives 153 nm cutoff line width. The cutoff line width 189 nm at 7.3 keV is comparable to the diffraction-limit performance [4] .

X-ray imaging of a Very-Large-Scale-Integration (VLSI) chip



- **Sample: SOPHIAS chip**
- **Aluminum lines had a minimum width of 300 nm and 600 nm thickness.**
- **Silicon chip has 500 μm thickness. This is significantly thicker than aluminum wire lines.**
- **The present detector successfully visualized these low contrast and deep sub-micrometer patterns [4].**

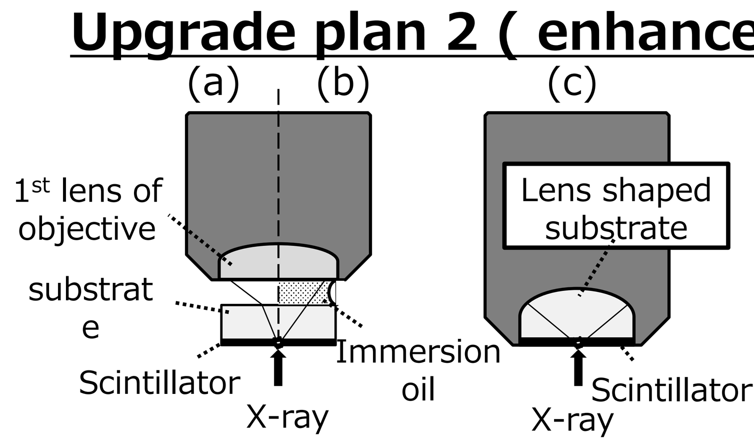
Fig. 6 (a) Circuit design drawing of metal layers in the 3 x 3 SOPHIAS imaging pixels
(b) X-ray transmission image acquired by the developed detector
(c) Line profile calculated for the image section depicted as a dotted rectangle in (b)

Upgrade plan 1 (enhancement of FOV)

We are planning to employ a large format CMOS image sensor and develop the dedicated objective lens.

	Present system	Upgrade system
Resolving power	200 nm line & space	**250 nm line & space**
FOV	133 x 133 μm²	**2,500 x 1,900 μm²**
Image format	2048 x 2048, 65 nm pixels	**14,192 x 10,640, 177 nm pixels**

Upgrade plan 2 (enhancement of spatial resolution)



We are planning to develop a solid immersion lens with super high NA 1.54 by installing the lens-shaped scintillator substrate as first lens. This optical design is capable of achieving sub-100 nm line & space visualization.

Fig. 7 Comparison of the objective lens structure.
(a) dry lens. (b) liquid immersion lens. (c) solid immersion lens

Summary

The developed indirect detector has successfully resolved 200 nm line-and-space patterns. This resolving power has successfully visualized wiring patterns and vias in the VLSI circuit.

References
[1] H. Yagi et al., Opt. Mater. 29 (10), 1258 (2007).
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[3] T. Kameshima et al., AIP Conf. Proc. 1741, 040033 (2016).
[4] T. Kameshima et al., Optics Letters 44, 1403 (2019)