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Fast Photoconductor CdTe Detectors for Synchrotron X-ray Studies

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Abstract

The Advanced Photon Source will be the brightest source of synchrotron x-rays when it becomes operational in 1996. During normal operation, the ring will be filled with 20 bunches of positrons with an interbunch spacing of 177 ns and a bunch width of 119 ps. To perform experiments with x-rays generated by positrons on these time scales one needs extremely high speed detectors. To achieve the necessary high speed, we are developing MBE-grown CdTe-based photoconductive position sensitive array detectors. The arrays fabricated have 64 pixels with a gap of 100 μm between pixels.The high speed response of the devices was tested using a short pulse laser. X-ray static measurements were performed using an x-ray tube and synchrotron radiation to study the device's response to flux and wavelength changes. In this paper, we shall present the response of the devices to some of these tests and also discuss different physics aspects that needs to be considered when designing high speed detectors.

Introduction

The Advanced Photon Source [1] (APS) at Argonne National Laboratory near Chicago, U .S. A., the European Synchrotron Radiation Facility [2] (ESRF) at Grenoble, France and the Super Photon Ring- 8 GeV [3] (SPring-8) at Harima Science Garden City, Japan are all third-generation insertion-device-based high-brilliance synchrotron radiation machines. The ESRF is operational, while the APS and SPring-8 will be operational in a few years. All of the above machines have electron/positron bunches whose widths are in the hundred picosecond range with interbunch spacing in the hundred nanosecond range. Further, the flux from a single bunch is sufficient for a large number of experiments. APS Undulator A operating at a gap of 16.5 mm with a beam current of 100 mA and an energy of 7 GeV has a first harmonic brilliance of 10^{18} photons/sec/0.1%BW/mrads^2/mm^2. Assuming a sample with a scattering power of 10^{-4}, there is sufficient flux to obtain data with a reasonable signal-to-noise ratio. Szebenyi et al. [4] have successfully demonstrated a quantitative analysis of Laue diffraction patterns recorded with a 120-ps exposure using an insertion device at the Cornell High Energy Synchrotron Source. Also for machine diagnostics studies, it is important to be able to measure the profile of a single bunch.

During normal operations, the storage ring of the Advanced Photon Source will be filled with 20 bunches of positrons. Each bunch will have a width of 119 ps with the interbunch spacing being 177 ns. Our intent is to measure the vertical profile of a single bunch and to be able to measure its time structure.

To be able to do this, we need detectors with a response in the picosecond range. Photoconductors have been used successfully as fast detectors where the speed of the device depends on the mobility and recombination of the material. InP has been used as an x-ray and ultraviolet radiation photoconductive detector with rise time <90 ps [5]. Also amorphous Si has been used successfully as a photoconductive detector of picosecond pulses [6]. Photoconductive devices are based on the principle that incident radiation changes the conductance of the material which is measured as the output signal [7]. Mercury Cadmium Telluride has been used routinely in infrared detectors in which the percentage of mercury defines the lowest cutoff wavelength of interest. The band gap of CdTe is 1.6 eV, sufficient to be used without mercury as a photoconductor for the x-rays of interest (6-25 keV). X-ray bunch lengths have been measured at the Cornell Electron Storage Ring (CESR) using an x-ray sensitive photoconducting detector [8]. Rossa et al. [9] have successfully used a CdTe detector to measure the profile of a single bunch at the Large Electron Project (LEP) at CERN.

Figure 1 is a diagram of the device we designed to measure the intensity profile of the x-ray pulse radiated from a single bunch of positrons. Each pixel consist of two electrodes with a gap between them. A bias is applied across the two electrodes, and the current is measured as a function of incident radiation on the gap. The thickness of the gap semiconductor depends on the maximum energy of the x-rays one wishes to stop. Every incident x-ray photon generates electron-hole pairs that change the conductance, which is measured as a change in current flow through the external circuit. The array consist of 64 pixels that are separated by a 100-μm gap.

For this study, a 10-µm-thick (111)B CdTe layers were grown by Molecular Beam Epitaxy (MBE) on (100) orientation of a Si substrate. Double crystal rocking curve (DCRC) full width at half maximum (FWHM) of these layers ranges from 500 to 1000 arcsecs. Because the resistivity of MBE-grown CdTe layers is far higher than that of the substrate, the Si substrate has to be removed in order to prevent the generated current conduction through it. The MBE-grown CdTe on Si was epoxied onto glass and the Si substrate was chemically etched away in KOH based etchant. X-ray diffraction measurements were made on those layers and DCRC FWHM of the interface between CdTe and Si was slightly higher. This was expected because of large (14%) lattice mismatch between (111)B CdTe and (100) Si. Array detectors of 64 photoconductors were fabricated using a conventional photoresist process and lift-off technique. The gap sizes are 5-µm to 50-µm with 100-µm spacing between two adjacent devices. For the contact metal, 1-µm Au and 0.1-µm Ni were subsequently sputter deposited. The dark current at 20V was as low as 2 nA to 50 nA for 20-µm-gap photoconductors, depending on the CdTe crystal quality.

Temporal Response Measurements

The temporal response of a 20-µm-gap CdTe photoconductor was measured with a mode locked Ti: Sapphire laser. The pulse width was 100 fsecs and has 500 pJ of energy. The measurement was made using a Tektronix CSA803 sampling oscilloscope that had a 20-GHz bandwidth sampling head. The results are shown in Fig. 2. The response curve has a width of 47 psecs with a rise time of 35 psecs. Considering the fact that the layer is 10-µm thick and the laser wavelength is long enough to penetrate deep into the layer, such fast response is surprising. In fact, the CdTe layer is single crystalline and DCRC FWHM is as good as 550 arcsecs. Therefore the carrier mobility is expected to be excellent. The high-density point defects in the as-grown MBE CdTe layer seem to contribute to the fast response of the photoconductor.

Spatial Measurements

The measurements for the spatial resolution of the CdTe photoconductor array were carried out using a pulsed laser and CW tube x-rays. The laser pulse with a 0.53-μm wavelength was obtained from a second harmonic generator of an Nd:YAG laser. The diameter of the output aperture was 1.5 mm. The CdTe photoconductor array was placed in the center of the beam and the response of each pixel was measured. The results are shown in Fig. 3. The FWHM of the response curve is about 500 μm. It was previously observed that the photoconductor response is linear from the threshold power of the laser. Therefore the decrease in the spacing of the response curve FWHM is probably due to the threshold of the second harmonic generation of the Nd:YAG laser. This response curve clearly represents the actual laser beam profile. Similar spatial response were observed from a tube x-ray beam. Fig. 4 shows the intensity profile as a single pixel is scanned across the x-ray beam. The FWHM measured from the exit slits of the x-ray generator of 750 μm corresponds to that of the slit setting. A second slit of width 300 μm was placed in front of the photocondutor, and again the detector measurement corresponded with the slit setting.

Using white radiation from a sealed tube x-ray generator, the linearity of the device with respect to increase in current as a function of tube energy was measured. As seen in Fig. 5, the curve is not very linear at low currents. This behavior could be attributed to the fact that the test was not done using monochromatic x-ray radiation.

Discussion

To perform time-resolved experiments from a single bunch of positrons from the storage ring, one needs detectors that have responses in the few-hundred-picosecond range and higher. The temporal resolution of the current CdTe photodetector should suffice. The pixel sizes can be reduced or increased with minimal changes in the temporal response of the detector. To be able to measure the horizontal (temporal) width of a single bunch of positrons, one needs a detector with a better time response. The pulse width of a photoconductor is proportional to the charge-carrier lifetimes, and its amplitude is proportional to its mobility. Studies have shown that the resolving time of photoconductive detectors improves dramatically after the device is irradiated with neutrons.[10] The neutron treatment decreases both the carrier lifetime and mobility, resulting in faster response of the detector and a lowering of the signal. One has to balance the two effects such that a device can be designed that has a time-resolution in the few-picosecond range with a reasonable output amplitude.

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Figure Captions

Fig. 1 Layout of the CdTe photoconductor for vertical profile measurements

Fig. 2 Temporal resolution obtained using a 100 fsec, 500 pJ pulse from a Ti:Sapphire laser.

Fig. 3 Spatial Resolution of a 64 element CdTe photoconductor using a 0.53 µm wavelength pulse of a Nd:YAG laser. Note that the pulse width (550µm) is smaller that the output aperture (1500µm) of the laser.

Fig. 4 Intensity profile of a single pixel scanned across two exit slits from a Mo sealed tube x-ray generator.

Fig. 5 Linearity test where intensity measured as a function of current for different power setting of a Mo sealed tube x-ray generator.

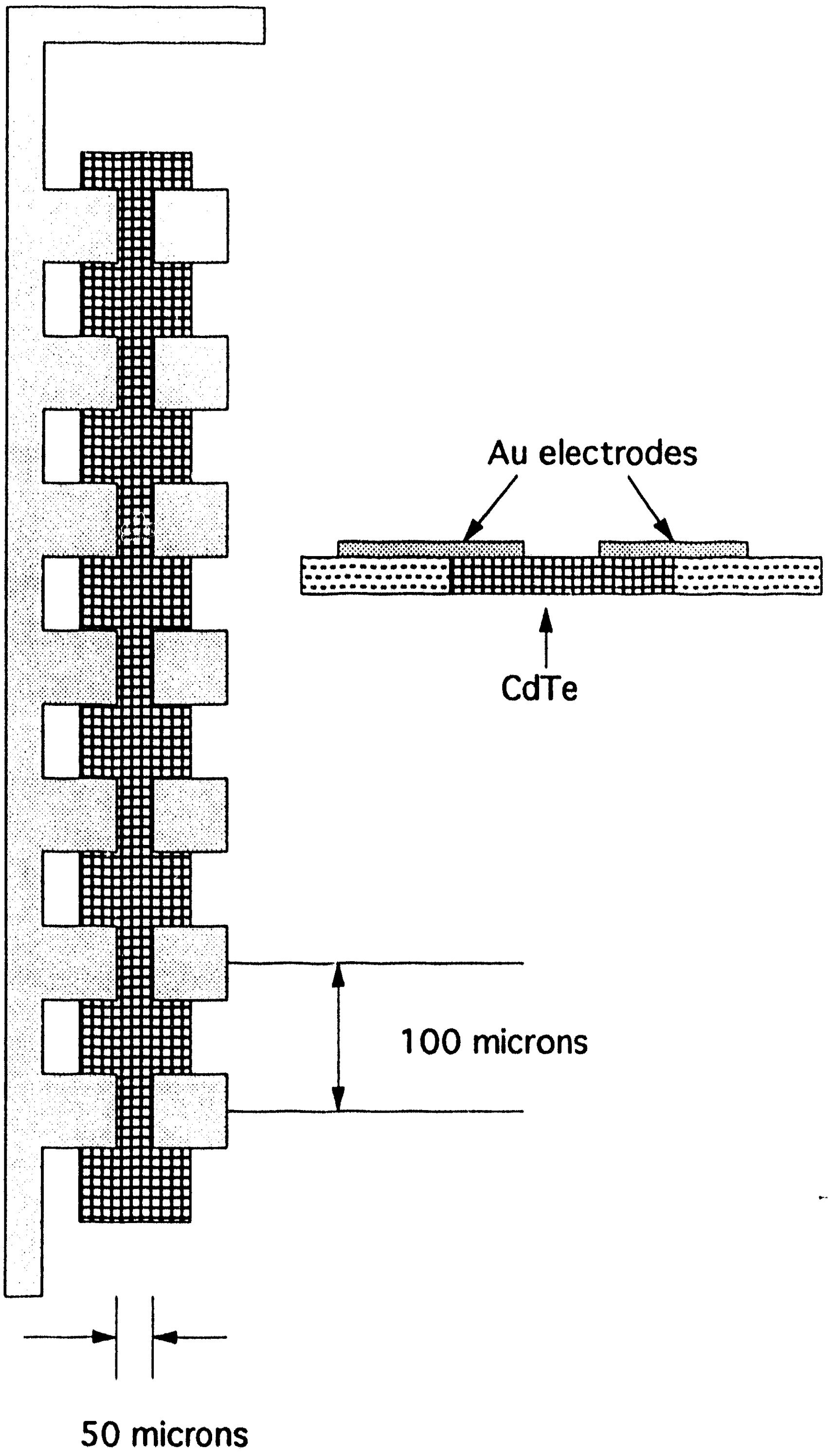
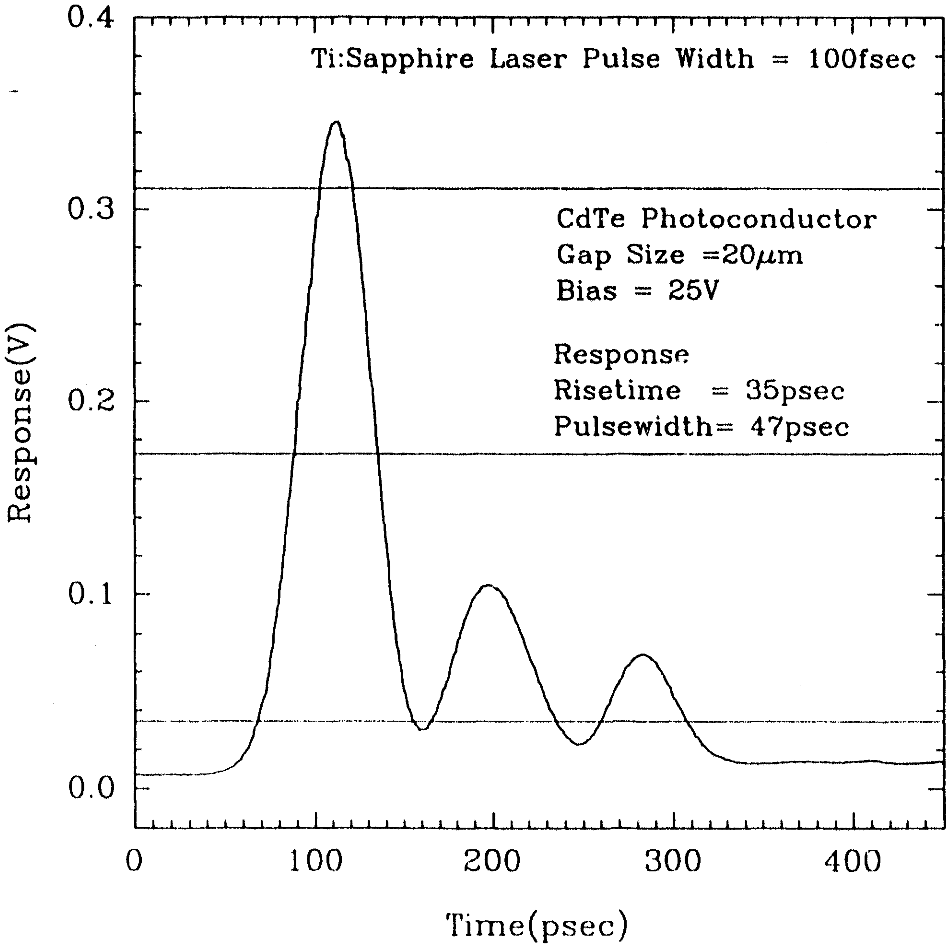
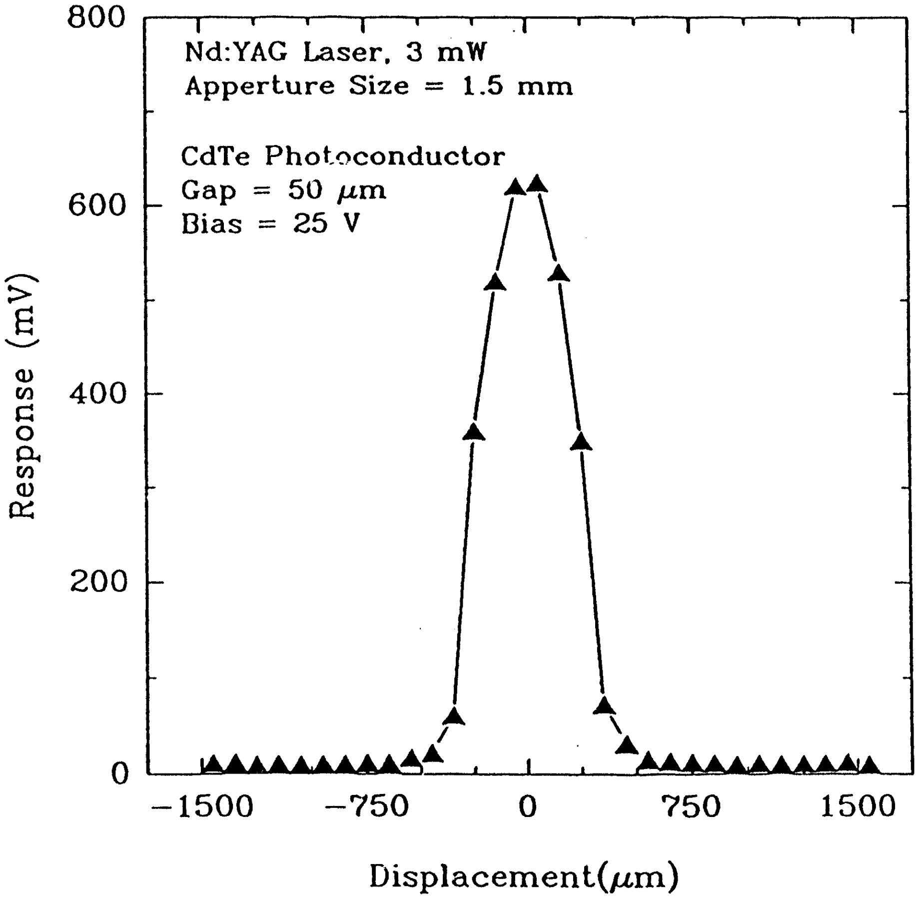


Fig 1



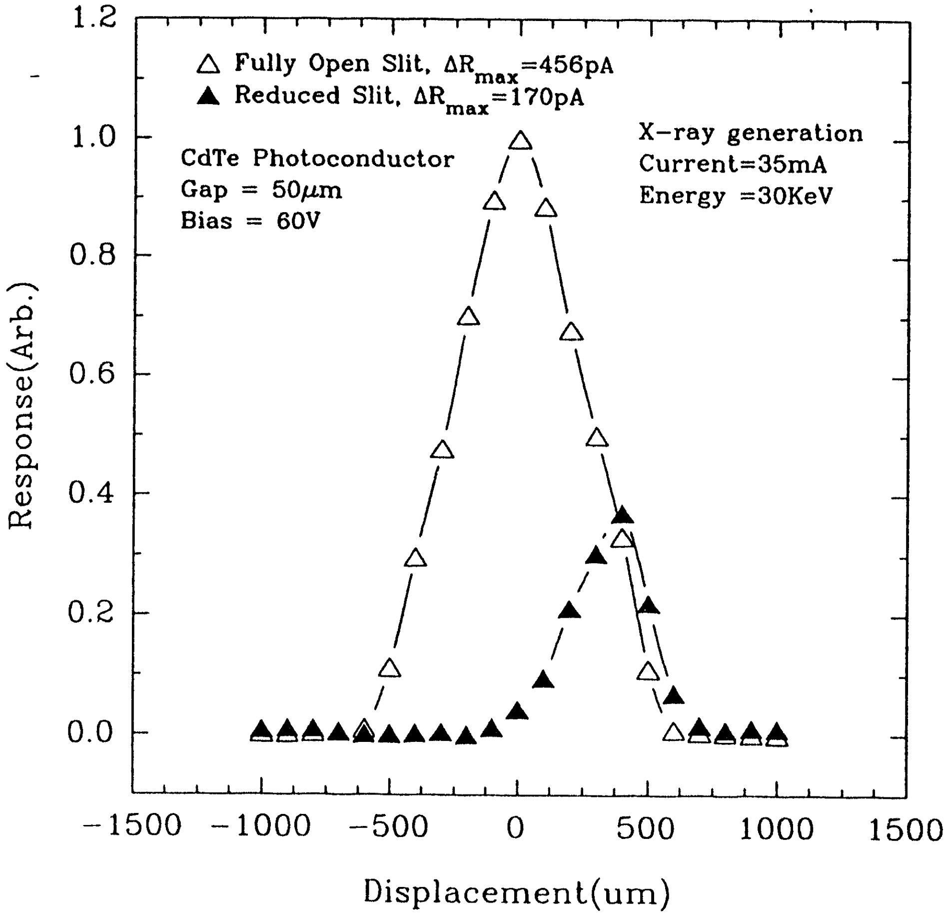
0.4
0.3
0.2
0.1
0.0
Response(V)
0
100
200
300
400
Time(psec)
Ti:Sapphire Laser Pulse Width = 100fsec
CdTe Photoconductor
Gap Size =20μm
Bias = 25V
Response
Risetime = 35psec
Pulsewidth= 47psec

Fig 2



Nd:YAG Laser, 3 mW
Apperture Size = 1.5 mm
CdTe Photoconductor
Gap = 50 μm
Bias = 25 V
800
600
400
200
0
Response (mV)
−1500
−750
0
750
1500
Displacement(μm)

Fig 3



1.2
1.0
0.8
0.6
0.4
0.2
0.0
Response(Arb.)
△ Fully Open Slit, ΔR$_{max}$=456pA
▲ Reduced Slit, ΔR$_{max}$=170pA
CdTe Photoconductor
Gap = 50μm
Bias = 60V
X-ray generation
Current=35mA
Energy =30KeV
−1500
−1000
−500
0
500
1000
1500
Displacement(um)

Fig 4

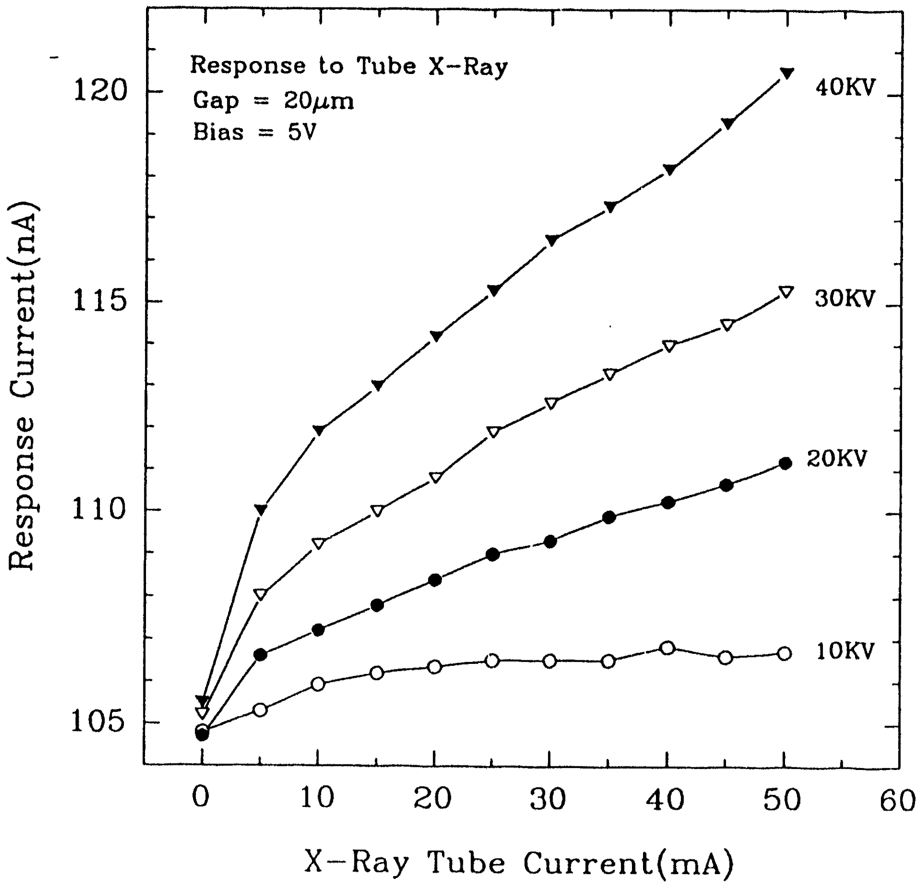

Response to Tube X-Ray
Gap = 20μm
Bias = 5V
40KV
30KV
20KV
10KV
120
115
110
105
Response Current(nA)
0
10
20
30
40
50
60
X-Ray Tube Current(mA)

Fig 5

END

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