● Aronix sheet NIR series for IR sensor covers and filters

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1. Introduction

Highly sensitive sensing and communication technologies are being actively developed to realize an Internet of Things (IoT) society, also called the fourth industrial revolution[1]. In the automotive field, automakers are steadily developing fully autonomous driving systems that utilize artificial intelligence, communication, and sensing technologies.

Table 1: Levels of autonomous driving

Level	Definition	Driver state
1	Driving assistance	Hands-on
2	Advanced driving assistance	Hands-off
3	Autonomous driving under specific conditions	Eyes-off
4	Fully autonomous driving under specific conditions	Brain-off
5	Fully autonomous driving	Brain-off

Table 1 lists the levels of autonomous driving as indicated in SAE International Standard J3016. Up to Level 2, a human drives the car, while Level 3 and above assume the system takes over (eyes-off, brain-off). As of 2021, Honda's Legend has achieved Level 3 in commercial vehicles (**Figure 1**).

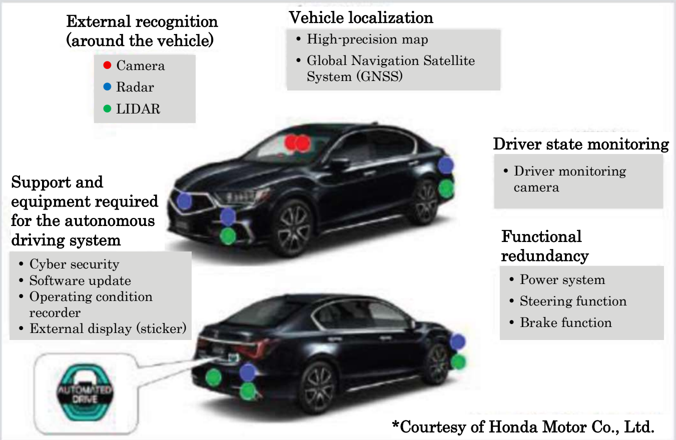

Figure 1: Components of the autonomous driving system (Ministry of Land, Infrastructure, Transport and Tourism; November 2020)

The processes required for autonomous driving can be divided into cognition, judgment, and operation. Sensing, which controls cognitive functions, is particularly essential. Particularly for Level 3 or higher autonomous driving, localization (vehicle positioning) technology and obstacle recognition technology based on it are required[2),3)].

The sensors currently under consideration for autonomous driving can be broadly classified into three categories: cameras, which detect images using visible light similar to the human eye; millimeter wave radar; and Light Detection and Ranging (LIDAR), which uses near-infrared laser light. As shown in **Table 2**, each sensor has its own set of advantages and disadvantages, making it difficult to recognize complex environments with a single sensor. For this reason, multiple sensors are being combined to improve detection reliability, and efforts are also underway to enhance the detection capabilities of each individual sensor.

Table 2: Comparison of in-vehicle sensors

Properties	Sensor/detection wavelength		
	Camera 400-800 nm	Millimeter-wave radar 4-13 mm	LIDAR 850-1600 nm
Spatial resolution	Good	Fair	Good
Distance	Fair	Good	Good
Weather	Fair	Good	Fair
Nighttime	Fair	Good	Good
Identification of objects on the road	Good	Fair	Good
Cost	Good	Good	Fair

Because LIDAR uses infrared lasers, it excels at nighttime detection when cameras have difficulty detecting objects on the road, such as cardboard boxes, that easily absorb millimeter waves. LIDAR also has a high spatial resolution, allowing it to detect the distance and bearing of an object in three dimensions.

For these reasons, LIDAR is regarded as an essential sensing technology for detecting changes in road conditions and identifying free space, both of which are required for Level 3 and higher. The LIDAR market is expected to grow from 3.4 billion yen (in 2020) to 1 trillion yen (in 2040)[4)].

LIDAR consists of a near-infrared laser oscillator and optical components, including a photodetector and an optical deflector, as well as a filter that blocks noise-causing visible light, and a cover material that protects the housing from flying objects, such as pebbles (**Figure 2**).

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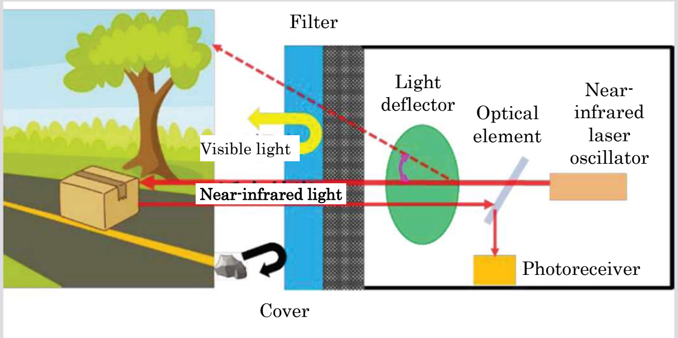

Figure 2: LIDAR configuration

Existing LIDAR optical deflectors are mechanical, large and heavy, and expensive due to the large number of components, which poses a barrier to widespread adoption[5)]. Therefore, developments to reduce size and cost are focused on optical deflection and detection technologies (**Table 3**). Non-mechanical (solid-state) laser deflection, which uses MEMS mirrors and other components to reduce the number of parts, has become the mainstream method of deflecting lasers. Currently, the mainstream detection method is Time of Flight (TOF), which calculates the distance based on the time between the transmission and reception of a laser beam. However, studies are underway to develop practical applications of the practical use of the Frequency Modulated Continuous Wave (FM-CW) system, which can simultaneously detect position and speed with high accuracy using the phase difference of laser beams.

Table 3: Classification and characteristics of LIDAR systems

	Classification	Method	Characteristics	Issue
Light deflection method	Mechanical	Rotating mirror	Existing	Large High cost
	Non-mechanical	MEMS, etc.	Compact	Narrow deflection angle
Detection methods and infrared rays	TOF	Pulse 905 nm	Low cost	Low resolution
	FM-CW	Continuous wave 1350, 1550 nm	High resolution	High cost

For autonomous driving on highways, it is essential to improve the sensitivity at long distances of 100 m or more, and LIDAR is therefore required to have even higher sensitivity.

Naturally, the covers and filters that make up LIDAR should also be made of materials that enable them to be smaller, lighter, and more sensitive.

We developed the ARONIX Sheet NIR Series, which reduces the number of parts by integrating the cover and filter. This paper presents the evaluation results of their properties and processability.

2. Performance as a cover material

In addition to abrasion and impact resistance against flying objects, such as pebbles, in-vehicle LIDAR covers must also withstand the heat generated by the laser oscillator inside the LIDAR housing.

Table 4 shows the evaluation of the various properties of the ARONIX Sheet NIR Series. Even NIR without a hard coating had a pencil hardness of 4H, while NIR-HC with a hard coating on both sides had a high scratch resistance of 6H. The results of the drop weight impact test were equivalent to those of chemically strengthened glass. The deflection temperature under load, an indicator of heat resistance, was over 250°C for ARONIX Sheet, compared to 140°C for polycarbonate resin (PC), which is commonly used as a cover material, confirming the high heat resistance of the ARONIX Sheet. The specific gravity is equivalent to that of common resins, and weight reduction can be expected when switching from glass covers.

Table 4: Physical properties of ARONIX Sheet NIR Series

	Chemical strengthening Glass [a)]	PC	ARONIX Sheet NIR	ARONIX Sheet NIR-HC [b)]
Specific gravity	2.4	1.2	1.2	1.2
Flexural modulus	83 GPa	2.5 GPa	3.3 GPa	3.5 GPa
Pencil hardness	> 9H	HB	4H	6H
Impact resistance [c)], 50% breakage height	50 cm	> 80 cm	40 cm	60 cm
Deflection temperature under load [d)]	> 250°C	140°C	> 250°C	> 250°C

a) Chemically strengthened layer thickness > 40 μm, reinforced on six sides
b) Double-sided hard coating
c) Test piece: t1 × 60 × 60 mm, support: inner diameter of Ø50 mm, weight: 40 g, tip diameter: R5 mm. The height of the falling weight was increased in 5 cm increments until the test piece cracked, and the height at which 50% of the test piece cracked was recorded. Number of test pieces: 25
d) JIS K6911, bending stress at 1.8 MPa, 120°C/h

The ARONIX Sheet NIR Series also exhibits high resistance to organic solvents, acids, and alkalis, such as brake fluid, which are assumed to be used around engine compartments (**Table 5**).

Table 5: Chemical resistance [a)]

Solvent	PC	ARONIX Sheet NIR
Methanol	Good	Good
Concentrated hydrochloric acid	Good	Good
Caustic soda: 48 wt%	Fair	Good
Tetrahydrofuran	Poor	Good
Acetic acid	Fair	Good
Xylene	Fair	Good
Dichloromethane	Poor	Good
Brake fluidb)	Fair	Good
Acetone	Fair	Good

a) Appearance after immersion for 24 hours at room temperature: Good: No abnormalities, Fair: Whitened, Poor: Dissolved
b) Genuine product of Toyota 2500H-A, immersed at 85°C for 24 hours

3. Performance as a filter

Filters for LIDAR must have high near-infrared transmittance and the ability to block visible light, which causes noise.

The transmittance of ARONIX Sheet NIR was 85% or higher at the wavelength of the infrared laser used for LIDAR, even without an anti-reflection (AR) coating (**Table 6**).

Table 6: Near-infrared transmittance of ARONIX Sheet NIR (t2 mm)

	Transmittance (%)		
	950nm	1310nm	1550nm
NIR	90.2	90.7	87.4

Figure 3 shows the spectra of the ARONIX Sheet NIR Series. We confirmed that sharp light-shielding can be achieved at any target wavelength by blending different dyes.

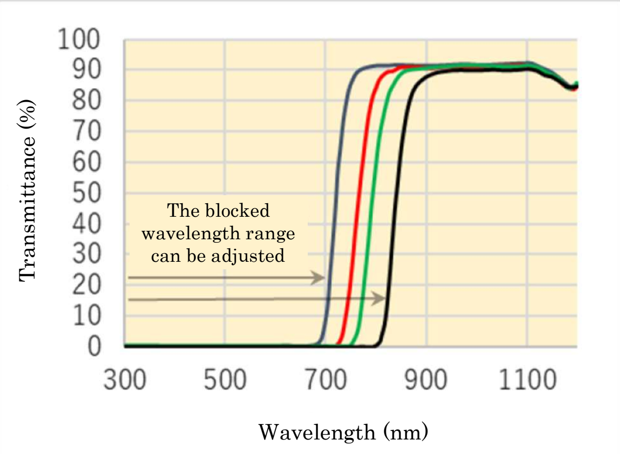

Figure 3: Spectral characteristics of the ARONIX Sheet NIR Series

For the FM-CW system, which detects the phase difference of a near-infrared laser, the filter and cover must have a low phase difference and a small phase difference distribution.

Table 7: Phase difference distribution in the infrared region (t2 mm)

	ARONIX Sheet NIR	PC [a]
Measured wavelength [b]	940 nm	850 nm
Average phase difference	9 nm	1849 nm
Max-Min	46 nm	2321 nm

a) Iupilon NF-2000, MITSUBISHI GAS CHEMICAL COMPANY, INC.

b) PA-300NIR (940 nm), WPA-200-NIR (850 nm), Measured by Photonic Lattice

Table 7 shows the evaluation of the surface phase difference distribution of the ARONIX Sheet NIR. Polycarbonate (PC), which has high impact resistance, is used as a cover for various optical components. However, as the table shows, both its phase difference and distribution are very large. In contrast, the ARONIX Sheet was optically homogeneous, with an average phase difference of about 9 nm at a thickness of 2 mm and a difference between the maximum and minimum values of only 46 nm.

4. Durability

Table 8 shows the changes in the surface hardness and transmittance of ARONIX Sheet NIR before and after 1,000 hours of durability testing that simulates in-vehicle LIDAR conditions.

Table 8: Pencil hardness and transmittance before and after the durability test

		Initial	Durability test conditions (1000 hours)		
			85°C85%RH	95°C	SW [a]
Pencil hardness		4H	4H	4H	4H
Transmittance (%)	905 nm	90.2	90.2	90.2	90.3
	1310 nm	90.7	90.4	90.8	90.9
	1550 nm	87.4	86.0	87.4	87.2

a) Sunshine Weather Meter: JIS A 6021 carbon arc, black plate temperature 63±3°C, 18-minute water spraying/120 minutes

No changes in pencil hardness or infrared transmittance were observed under either condition, confirming the high durability required for in-vehicle LIDAR.

5. Processability: Curved cover

As a resin, ARONIX Sheet NIR can be processed using general-purpose processing machines, such as laser cutters and NC routers, enabling fine planar machining that is difficult to achieve with glass.

However, LIDAR for wide-area sensing also requires a curved, 3D cover material to prevent differences in the optical path of infrared laser beams. We therefore studied manufacturing methods for curved covers using ARONIX Sheet NIR.

ARONIX Sheet NIR is a thermosetting resin. Unlike a thermoplastic resin like PC, it cannot be bent by pressing. Therefore, a master plate (R500 mm) for the curved cover was made by thermal curing in a curved glass mold. The resulting master plates exhibited high dimensional stability, with none of the springback observed when bending thermoplastic resins. The surface was also as smooth as that of the glass mold.

Furthermore, the curved ARONIX Sheet NIR did not crack when flattened under load, and returned to its original shape when unloaded. In other words, applying a load to the curved cover master plate and flattening it enables cutting with a general-purpose laser cutter or similar tool, allowing the curved cover to be cut to any desired size (**Figure 5**).

Figure 5: R500 curved cover

6. Processability: Surface treatment

Anti-reflection (AR) treatment is one of the methods to further increase the transmittance of infrared rays. Therefore, the AR films were deposited by sputtering onto ARONIX Sheet NIR (**Figure 6**). The deposited AR film showed good adhesion, with no peeling observed either initially or after immersion in hot water at 85°C for 60 minutes. The design of the AR film also allowed the cover surface to have a similar structural color to that of the vehicle body, making it less noticeable.

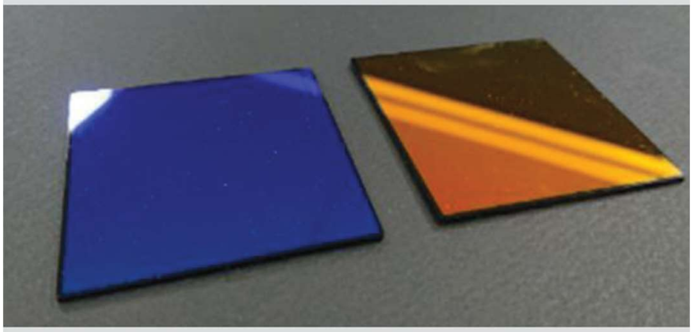

Figure 6: AR film deposition product

7. Processability: Function as a heater

Because in-vehicle LIDAR is installed outside the vehicle, ice and snow are expected to adhere to it in cold regions. The ice and snow on the front of the cover must be removed because they reduce the sensitivity of LIDAR and make it difficult for infrared rays to penetrate. In addition to mechanical devices, such as spraying windshield washer fluid, another method of removing ice and snow is to heat and melt it with a heater. In this study, a cycloolefin polymer (COP) film coated with an ITO transparent conductive film was bonded to ARONIX Sheet NIR using an optically clear adhesive (OCA) to add a heating function, and its performance was verified (**Figure 7**).

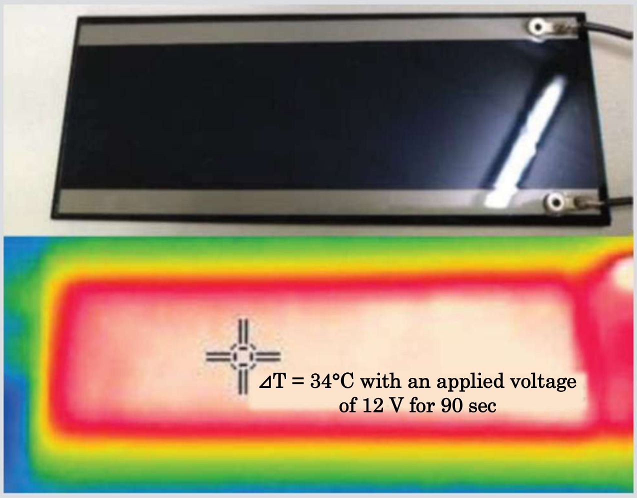

Figure 7: Heater function implemented with ITO film [a]

a) COP/ITO film: 30 Ω/sq, made by GUNZE LIMITED, prepared by Heat Lab Corporation

The transmittance with the ITO film laminated was 83.4% (905 nm). The heater exhibited good heating performance with a voltage of 12 V and a temperature rise of ⊿T = 34°C in 90 seconds.

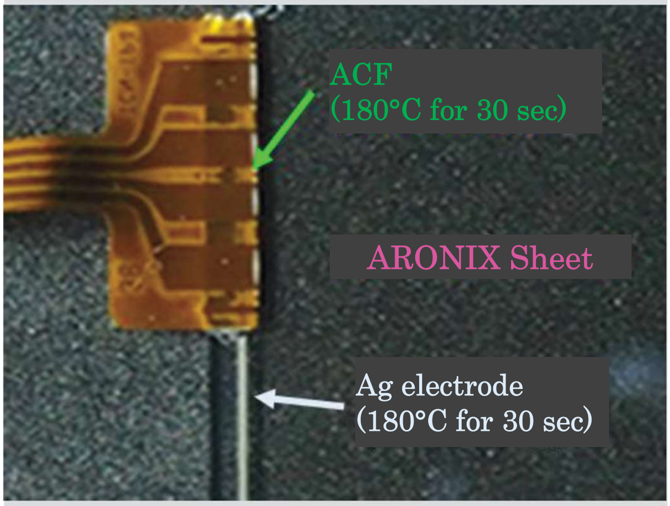

Figure 8: Direct formation of conductive circuit patterns on the sheet

Because ARONIX Sheet NIR has high heat resistance, Ag paste and ACF (anisotropic conductive film), which require high-temperature processing at 150°C or higher, can be used. Moreover, conductive circuit patterns can be formed directly on the sheet (**Figure 8**).

We are currently developing a heater-integrated cover and filter with high transmittance and fewer components by forming conductive circuit patterns directly on the ARONIX Sheet NIR.

8. Summary

ARONIX Sheet NIR we developed was demonstrated to have high abrasion and impact resistance as a cover material, as well as high infrared transmittance and visible light blocking performance as a filter. Its low phase difference and phase difference distribution are expected to be applied to the FM-CW system, which is gaining attention as a next-generation LIDAR system.

General-purpose processing machines can also cut ARONIX Sheet NIR into curved shapes, which is expected to reduce processing costs.

Because its heat resistance can be employed to create conductive circuits directly on the sheet, the integration of a heater mechanism can also be expected. Reducing the number of components such as OCA through integration not only enables LIDAR miniaturization, but also improves infrared transmittance, or in other words, sensitivity.

Going forward, we will work on improving the physical properties of the sheet and integrating more functions by leveraging the characteristics of ARONIX Sheet NIR. We also plan to propose using the sheet as a new component for compact, lightweight LIDAR systems that could be used not only in vehicles, but also in drones and other applications.

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