

Review of literature & Experimental Techniques

Solar thermal technology has gained considerable attention in both academia and industry as a promising alternative renewable energy source for widespread applications. Solar energy has a huge potential to fulfill the continuously growing energy demand. The heart of solar thermal technology is its receiver on which a spectrally absorber coating is employed to efficiently absorb the incident solar radiation and converting into thermal energy with minimal thermal losses. This thermal energy can be used further in a number of applications ranging from heating and cooling to the power generation. The design of spectrally selective absorber requires an understanding of solar spectrum, which is briefly described in the following section.

2.1 Solar radiation spectrum

The solar radiation spectrum is mainly distributed over UV-Vis to NIR range, which is matched with black body radiation emission for 5777 K. The UV, Vis and NIR region consist of approximately 8.03 %, 46.41%, and 46.40%, respectively of solar radiation spectrum [Masters, 2004]. The solar radiation reaching earths' surface gets attenuated due to absorption and scattering in the ionosphere , ozone layer, and various ambient gases such as nitrogen, oxygen, moisture, carbon dioxide, moisture, and dust particle [Duffie and Beckman, 1991]. The solar constant (G_{sc}) is defined as solar energy received on earth surface outside its atmosphere at earth-sun mean distance per unit area, per unit time perpendicular to the direction of propagation and is $\sim 1367 \text{ W/m}^2$ [Duffie and Beckman, 1991]. Solar radiation is also characterized using Air mass (AM), which represents the relative path length travelled by radiation in atmosphere to the shortest path length i.e., when Sun is directly on overhead (AM0). The air mass $AM=1/\text{Cos}\theta$, where θ is zenith angle. The solar spectrum consists of two types of radiation: (i) direct or beam radiation, and (ii) diffuse radiation. The AM 1.5 represents the average solar spectrum, including direct and diffuse spectra received at the earths' surface [Masters, 2004]. **Figure 2.1(a)** represents Sun's position at AM0 and AM 1.5. At the earths' surface, standard Global solar spectrum AM1.5G (where G stands for global) is equal to 1000 W/m^2 . AM 1.5D (where D stands for direct) includes only the direct solar spectrum that reaches the earths' surface and is 963.56 W/m^2 [Liley, 2013]. **Figure 2.1(b)** shows the standard solar spectrum corresponding to the American Society for Testing and Materials (ASTM) at different air mass.

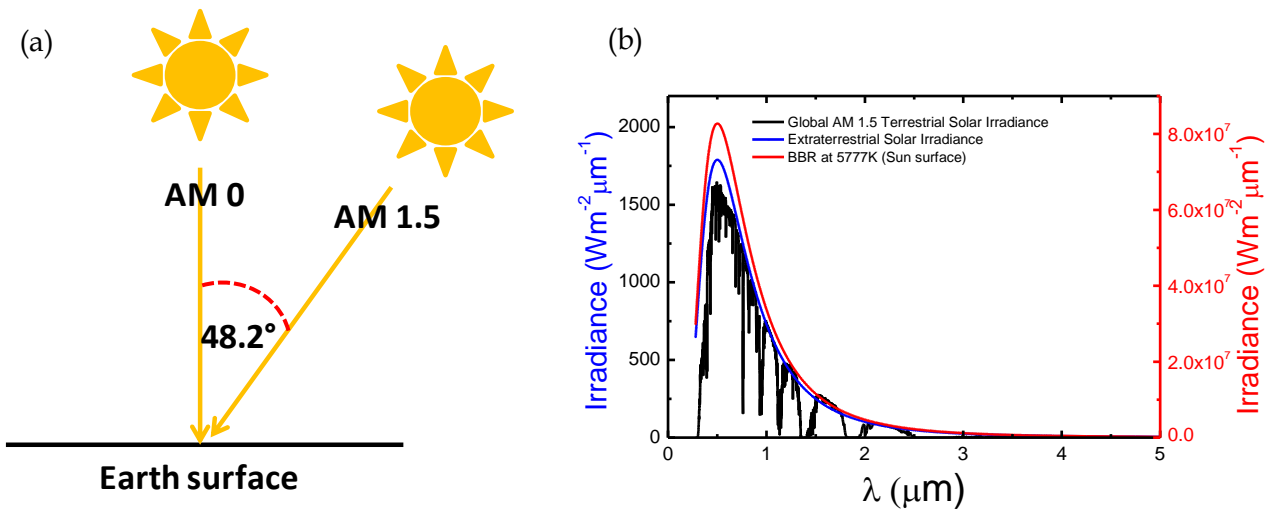


Figure 2.1 (a) Schematic representation for air mass ratio (AM) definition (b) Solar irradiance versus wavelength curve for AM1.5G terrestrial, extraterrestrial and black body radiation at 5777 K (sun surface Temp.)

2.2 Spectrally selective absorber coating

As per solar spectrum distribution, the solar radiations are mainly available in the UV-Vis-NIR range (0.2-2.5 μm) [Kennedy, 2002], as shown in **Figure 2.2**. This spectrum is drawn as per the American Society for Testing and Materials (ASTM) G173 for air mass 1.5 (AM 1.5). This solar spectrum suggests that a good solar absorber should absorb the solar radiation in 0.3 – 2.5 μm range. The absorption material gets heated simultaneously and thus, will start emitting the thermal radiation in the infrared region, i.e., 2.5 – 25 μm , following Planck's distribution [Duffie and Beckman, 1991]. Thus, to minimize the thermal losses, the spectrally selective absorber coating needs to have the minimum thermal emittance. That's why a spectrally selective absorber coating should exhibit high absorptance in the UV-Vis-NIR range (ideally 100%) and low thermal emittance in the infrared region (ideally ~ 0). However, a spectrally selective absorber coating structure with absorptance $\geq 95\%$ and thermal emittance $\leq 5\%$ is acceptable for possible solar thermal applications [Kennedy, 2002]. These spectral selective coatings are employed on the absorber tube of a receiver in solar thermal technology to efficiently harness the solar energy into thermal energy.

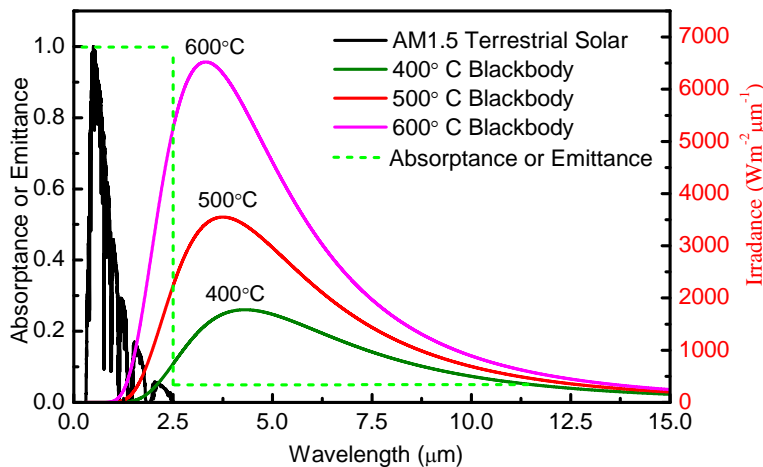


Figure 2.2 Solar spectrum at air mass 1.5 and black body radiation at temperature 400°C, 500°C and 600°C calculated using plank's law [Duffie and Beckman, 1991]. Green dash line represents ideal absorptance in Uv-Vis-NIR range and thermal emittance in IR range.

The ideal optical properties of a spectrally selective absorber are shown in **Figure 2.2**. With an increase in temperature, the peak of the thermal radiation shifts toward lower wavelength, and thus, a tradeoff between absorption and thermal emittance arises with a rise in temperature. With an increase in temperature, the absorption window starts reducing as thermal radiation starts shifting toward the low wavelength side, which means higher thermal losses in the case of higher operating temperatures.

Spectrally selective absorber is characterized by estimating solar absorptance (α) in UV-Vis-NIR range (0.3 - 2.5 μm) and thermal emittance (ε) in IR range (2.5 - 25 μm). The solar absorptance is defined as the fraction of incident energy absorbed by the surface. For an opaque material, the solar absorptance can be expressed in terms of total reflectance $R(\lambda, \theta)$ [Duffie and Beckman, 1991] as (equation 2.1):

$$\alpha(\lambda, \theta) = 1 - R(\lambda, \theta) \quad (2.1)$$

Where λ is the wavelength, and θ is the incidence angle with respect to reflecting surface normal. The solar absorptivity can be calculated using the solar spectrum $I_{SR}(\lambda)$ (Rredc, 2015) as (equation 2.2):

$$\alpha = \frac{\int_{\lambda_1}^{\lambda_2} (1 - R(\lambda)) I_{SR} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{SR} d\lambda} \quad (2.2)$$

where $\lambda_1 = 0.3 \mu\text{m}$, and $\lambda_2 = 2.5 \mu\text{m}$ represent the minimum and maximum wavelength limits for solar spectrum distribution in UV-Vis-NIR range, respectively.

Thermal emittance is also calculated to estimate the thermal loss from the spectral absorber surface. This is defined as the ratio of emissive power of a hot body with respect to that of the blackbody radiation at the same temperature. The hemispherical thermal emittance is considered due to the radiation-emitting in all direction [Tesfamicharel, 2000] and for an opaque surface, it is expressed as (equation 21.3):

$$\varepsilon(\lambda) = 1 - R(\lambda) \quad (2.3)$$

As per thermal emittance definition, the emissivity of a coating at temperature T is expressed as (equation 2.4)

$$\varepsilon(T) = \frac{\int_{\lambda_1}^{\lambda_2} (1 - R(\lambda)) B(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} B(\lambda) d\lambda} \quad (2.4)$$

Where $B(\lambda, T) = c_1 \lambda^{-5} / (e^{c_2/\lambda T} - 1)$ is blackbody radiation distribution against wavelength at temperature T , $c_1 = 3.743 \times 10^{-16} \text{ W}\mu\text{m}^4\text{m}^{-2}$ and $c_2 = 1.4387 \times 10^{-16} \mu\text{mK}$ are first and second Planck's radiation constants. $\lambda_1 = 2.5 \mu\text{m}$ and $\lambda_2 = 25 \mu\text{m}$ are lower and upper limits in IR range (2.5 - 25 μm).

2.3 Fabrication technique employed for spectrally selective absorber coating

The spectrally selective absorber coatings are deposited using various physical and chemical techniques such as physical vapour deposition, chemical vapour deposition, and solution route. The commonly used physical vapour deposition techniques are sputtering, evaporation and the example of solution routes are electrodeposition, and sol-gel derived spin, spray dip coating, and paint. In the following sub-section, we will be discussing some of the commonly used fabrication techniques, which are also utilized for the fabrication of spectrally selective coatings for the thesis work

2.3.1 Sputtering

Most of the spectrally selective absorber coatings are fabricated using sputtering, which is also being explored for commercial production of SSACs. This is a vacuum-based technique where target material, to be deposited, is etched by applying DC or RF power. In this process, energetic gaseous atomic particles collide with the target, and etching of the target surface starts. The etched particles are directed towards the substrate surface for deposition. The deposition rate can be controlled by varying different deposition parameters, such as deposition power, temperature, time, and working gas pressure. The major challenge in sputtering is the requirement of a high vacuum, which makes this system process complex and costly. However, the various process parameters, such as different deposition control parameters, sputtering becomes a common choice for depositing the desired composition of constituent material specially in case of metal-dielectric composite structures, which is one of the most common SSAC structures. Further, numerous SSAC structures can be deposited using co-sputtering and reactive sputtering. However, this technique may face scaling issues because of the high vacuum and structural geometries for depositing coatings on large surfaces. Such system requirements lead to complex geometries together with high cost. Cr-Cr₂O₃ cermet structure is deposited using this technique on nickel-coated SS substrate, showing absorptance ~ 0.92 and emittance ~ 0.08 at 100 °C [Fan and Spura, 2003, Fan, 1978]. Further, graded Cr-Cr₂O₃ cermet structure with absorptance ~ 0.90-0.92 and emittance ~ 0.04 at 100 °C are also reported [Teixeira et al., 2001]. Several transition metallic carbide and metal silicide structure on Ni and SS substrate were sputter deposited. This structure showed relatively lower absorptance ~ 0.76-0.80 but very low emittance ~ 0.02-0.03 [Harding, 1976, Harding, 1978, Sikkens, 1982]. A large number of graded metal carbide structures of SS-C, Cu-C, Cr-C, Fe-C etc., were reported as SSAC for solar thermal application in mid-temperature range [Selvakumar and Barshilia, 2012]. Harding et al. developed SS-C based coating with high absorptance ~0.94-0.95 and low emittance ~0.05-0.06 at room temperature [Harding, 1979]. Zhang et al. developed Al-AlN based structures, which showed absorptance ~ 0.95 and emittance ~0.05 at 80 °C [Zhang, 1999]. Another structure with Pt- Al₂O₃ multilayers on a quartz substrate is reported with absorptance ~ 0.95 and emittance ~ 0.08-0.20 at a much higher temperature 827 °C. This structure also showed high-temperature thermal stability up to 700 °C in air [Schön et al., 1994]. Al₂O₃/Ni, Cr, Ta, Pt, and Mo/ Al₂O₃ SSACs on glass substrates are reported with absorptance 0.89-0.95 and emittance ~ 0.14-0.25 at 537 °C. These structures also showed high-temperature stability up to 300-600 °C in air and up to 400-700 °C in vacuum [Thornton and Lamb, 1982]. Al_xO_y-Al-Al_xO_y SSAC on Cu and Mo substrates are reported with absorptance ~ 0.95-0.97 and emittance 0.05-0.08 at 82 °C [Barshilia et al., 2009]. NREL laboratory, USA, also reported high-temperature stable SSAC namely NREL #6A and NREL #6B using sputtering, showing absorptance ~0.95 and emittance ~0.08 for NREL #6A and 0.10 NREL #6B structure at 500 °C [Selvakumar and Barshilia, 2012, Kennedy and Price, 2005]. Recently Rodríguez-Palomo et al. reported Al₂O₃/Si₃N₄/MoSi₂-Si₃N₄/Inconel SSAC with high absorptance ~ 0.92 and moderate emittance ~ 0.13. This structure also showed good thermal stability in the open air up to 600°C, and thus, showing potential for commercial applications such as high-temperature CSP [Rodríguez-Palomo et al., 2018].

2.3.2 Evaporation

The evaporation techniques involve evaporation of source material by different means of heating the source material in a vacuum or low-pressure environment, transportation of evaporated atoms or molecules to the substrate where it starts condensing to form a thin film. Thermal and electron beam evaporation techniques have been utilized to fabricate SSACs. So far, several evaporations based SSAC have reported. Niklasson et al., demonstrated Co evaporated Co- Al₂O₃ cermet structure with Al₂O₃ as anti-reflection coating. This structure showed absorptance ~ 0.94 and emittance ~ 0.04 at 100°C [Niklasson & Granqvist, 1984]. Evaporation based other metal-dielectric structures such as Ag-Al₂O₃, Au-Al₂O₃, Cr-Al₂O₃ also showed good absorption and emission properties in the desired wavelength ranges, making them suitable for solar thermal application [McKenzie, 1979]). Peterson et al., reported semiconductor based selective absorber of Te and Se on Au, Al and Cu substrates with absorptance ~ 0.90-0.92 and emittance ~ 0.03-0.06 at 100 °C [Peterson and Cocks, 1980]. These SSACs were reported for mid-temperature range applications. There are few reports on high-temperature SSACs using evaporation techniques. Schmidt and Park developed Al₂O₃-Mo-Al₂O₃ structures on Mo substrate, demonstrating moderate absorptance ~ 0.85 and emittance ~ 0.22 at 1000 °C together with thermal stability at 920 °C for 500 hours [Schmidt & Park, 2008]. Ni- Al₂O₃ and Pt-Al₂O₃ co-evaporated cermet coating on quartz substrate were reported by Craighead et.al. These structures exhibited absorptance ~ 0.94 and emittance ~ 0.10 at 150 °C [Craighead & Buhrman, 1977, Craighead et al., 1979, Craighead et al., 1981]. Ni- Al₂O₃ deposited on Cu, and Ni substrate showed better thermal stability in air up i.e., up to 400 °C for Cu and 500 °C for Ni substrate case. Pt-Al₂O₃ SSAC showed better thermal stability, and a graded Pt-Al₂O₃ cermet structure with SiO_x as the antireflection layer on top showed enhanced absorptivity of ~ 0.98 [Craighead et al., 1981]. Some other structure e.g., graded Mo-Al₂O₃ by Nyberg and Buhrman, graded Ni-MgO, Ni-SiO₂, and Ni-MgF₂ cermet coating structures were also explored for high-temperature applications using evaporation [Nyberg & Buhrman, 198, Okuyama et al., 1979. Even though various structures were reported using this technique, this technique has limitations for scaling i.e., coating on large and arbitrary surfaces [Selvakumar and Barshilia, 2012].

2.3.3 Pulsed laser deposition

Pulsed laser deposition (PLD) technique is employed successfully to deposit thin film for numerous optical coatings, high-temperature superconducting films, and magnetic resistive coatings [Cheung, 1994, Dijkkamp et al., 1987, Jin et al., 1994, Tang et al., 2010]. Few cermet based selective solar absorber coatings are fabricated using PLD. For example, Ti-Al₂O₃ cermet layer is fabricated using PLD with very low reflectance in low wavelength region (Visible) and high reflectance in the long-wavelength region (IR range) [Chen et al., 2008]. However, this technique is not suitable for the uniform deposition of thin films on the large surface area [Cheung, 1994]. This may be the reason behind the non-availability of much literature on the development of spectrally selective coatings using the PLD technique.

2.3.4 Ion plating

To deposit films using this technique, a continuous beam of energetic atomic particles strike on the substrate. The thin film deposition using this technique will rely on mass and flux of striking particles. The ratio of striking particles to particles depositing is also important for thin-film structures. TiAl/TiAlN/TiAlON/TiAlO based structure on SS and Cu substrate are fabricated using the ion plating technique. This selective absorber is reported to have absorptance ~ 0.90 and thermal emittance ~ 0.08-0.09. This coating structure is also thermally stable in an open environment up to 650°C for an hour. However, long term thermal stability is not reported [Hao et al., 2009]. This technique is also limited for large scale coating applications because of the high vacuum and complex system requirement for arbitrary surfaces.

2.3.5 Arc Evaporation

In this technique, a dc arc, at low voltage and high current, is employed to evaporate the anodic or cathodic material. The evaporated material is then deposited on the substrate. The ionized evaporated material is accelerated and directed towards a biased substrate. Various metallic and compound layers are reported for different applications. Due to macroparticles emission, the optical/microstructural properties of the fabricated films are affected. Cermet based C:H-SS and Al-AlN spectrally selective coatings on the metallic substrate are reported with the absorption of 0.90 and thermal emittance of 0.06 at room temperature (RT). The absorption > 0.95 is achieved with the use of a-C:H antireflection coating on top of a-C:H-SS coating, together with low thermal emittance [Yin et al., 1996].

2.3.6 Chemical vapor deposition (CVD) and plasma-enhanced CVD

In chemical vapor deposition technique, atoms or molecules of the relevant materials are achieved after the decomposition of respective materials/precursors at high-temperature and transported using carrier gas to deposit on the substrate. The reduction of depositing atoms or molecules is achieved using hydrogenous of the environment. In the case of plasma-enhanced deposition, plasma-induced decomposition takes place, followed by the reaction to deposit the respective coatings on the substrate [Mattox, 1997]. Generally, CVD technique is employed to deposit oxide and non-oxide semiconductor thin films for electronic applications. Further, transition and few other metal-based carbides, nitrides, borides, and oxides are explored to fabricate solar absorber layers [Lampert, 1979, Kennedy, 2014]. The multilayer based structures consisting of metal and SiC:H alternate layers are reported to have good spectral selective properties in high-temperature range with an absorptance of 0.92 and thermal emittance of 0.08 at 500 °C [Soum-Glaude et al., 2013]

2.3.7 Electrodeposition

Electrochemical or electroplating is an electrolytic process, where electric current is used to migrate the source metal ion from solution to deposit onto the cathode, i.e., substrate. This process has been used to prepare cermet based spectral selective absorbers. Black chrome was the first SSAC, fabricated using electrochemical deposition [Cao et al., 2014]. The electrochemical deposition process is affected by the current density, bath concentration, deposition time, and temperature, together with the choice of electrodes. It has been observed that most of electrochemically deposited SSAC are developed at lab scale, and only limited coatings have shown potential to develop SS absorber tubes for field applications [Kennedy, 2002]. Though electroplating has certain advantages in terms of ability to coat on large areas, normal ambient coating conditions, and also cost-effective, there are some issues such as environmental toxicity, and large current requirements. Further, developed coatings are relatively thicker, exhibiting high absorptance but also high thermal emittance. This may be the main reason behind the fewer acceptances for adopting this process for efficient absorber coatings for solar thermal applications.

2.3.8 sol-gel Technique

It is a wet-chemical process where initial materials/precursors form a colloidal solution after hydrolysis, followed by poly-condensation. The film deposited using this technique depends on the viscosity of the solution and pre/post thermal treatments. Generally, alkoxides of metals are used for gel formation. The different solvents can be used to control the viscosity of the solution. This technique can be employed for coating on different receiver tubes irrespective of their shape and size. Also, this technique does not have any specific vacuum or temperature requirement. So this process is very viable for the development of commercial SSACs on receiver tubes as compared to other fabrication methods. The sol-gel based different

techniques include spin, spray, dip, and paint-based coating processes. Some of these are described in the following subsection.

2.3.8.1 Spin and Spray Coating:

Spin coating technique is an established sol-gel based deposition technique and is widely used to deposit oxide thin films at lab scale. This coating process does not require any sophisticated instrumentation and is one of the simplest deposition techniques. Also, the material/precursor requirement is very low as compared to other techniques. The deposition can be performed at open-air conditions. Nanostructured carbon-nickel oxide matrix-based SSACs are being fabricated using this technique [Katumba et al., 2008]. C-NiO based SSAC with absorptance up to 0.90 on large-area is deposited using spray coating [Roro et al., 2011]. The spin or spray coating technique is used to improve the thermal stability of CuO/Cu based spectral selective coatings by adding other components. CeO₂/Rh₂O₃/CuO/Ag, CeO₂/AgPt/CuO/Rh/Rh₂O₃/Ag/Pt, and CeO₂/CuO/CoO/Mn₂O₃/Pt SSACs are developed using either spin or spray process with absorptance ~ 0.9, 0.86-0.88, 0.88-0.92, and emittance values ~ 0.1, 0.1, 0.06-0.12 respectively. Cermet composite of quasicrystal like AlCuFe, AlCuFeCr in TiO₂, Y₂O₃, ZrO₂, Al₂O₃, SiO₂, V₂O₅, WO₃, Ta₂O₅, CeO₂ and Nb₂O₅ dielectric matrices are developed as SSACs using spin or spray coating with absorptance ~ 0.86-0.92 and emittance ~ 0.031-0.05 [Kennedy, 2002]. Other cermet structures, e.g., ZrN, CrN, HfN, TiN, or Ti_xAl_{1-x}N in alumina dielectric matrix are developed using spin or spray coating, and the optimized process is patented [Thornton J.A. and Lamb, 1987]. Spin coated NiCo₂O₄, CuCo₂O₄, (NiFe)Co₂O₅ spinel coatings are reported with absorptance ~ 0.91, 0.89, 0.88, and emittance ~ 0.30, 0.22, 0.34 at 80 °C. These structures exhibited relatively lower absorptance and higher emittance values. However, due to the ease of deposition using spray coating and potential for scaling, these coating structures are important to explore further for enhancing their spectrally selective properties. NiAlO_x cermet structure on SS substrate using spray pyrolysis technique is reported with the optimized absorptance and emittance values ~ 0.785 and 0.083, respectively. Tulchinsky et al. reported spray coating based new solar absorber Cu_{0.44}Ti_{0.44}Mn_{0.84}Fe_{0.28}O₃, which showed absorptance ~ 0.97 and 0.94 at 650 °C and 750 °C, respectively [Tulchinsky et al., 2014]. Spin Coated Ag-Silica metastructure SSAC structure on Cu is also reported with high absorptance ~ 0.95 and low emittance ~ 0.06 [Lee et al., 2017]. One major limitation of the spin coating technique is the scaling for large area deposition, whereas, spray coating can be utilized for large scale coating and may be suitable for commercial production.

2.3.8.2 Dip Coating:

Sol-gel based dip coating process is one of the oldest commercial methods. Schott et al. filed and got the first patent for silica thin film based on this process in 1939 [Lee et al., 2017]. Currently, sol-gel dip coating is being explored for various applications such as the protection layer, in electronic industries for sensors and membranes, and also for SSACs [Brinker and Hurd, 1994, Subasri et al. 2016]. CuFeMnO₄/silica films were fabricated using sol-gel dip coating. This film showed good absorptance ~ 0.93 but relatively higher emittance ~ 0.29-0.39 [Kaluža et al., 2001]. Multilayered nanocrystalline Cu-Co-Mn-Si-O based structures are fabricated using this technique, showing absorptance ~ 0.95 and emittance ~ 0.12 at 100 °C. This coating showed better thermal stability in the air up to 360 °C compared to the traditional black chrome structure. A thin homogenous layer of this black absorber was coated on 2 m long SS tube, and thus showing its potential towards practical application [Joly et al., 2013]. A homogenous thin film coating of CuMnO_x on Al and SS substrates was fabricated using a single step dip-coating technique. Absorptance and emittance values for this coating Al substrate are ~ 0.80 and 0.06, respectively. Cu_{1.5}Mn_{1.5}O₄ with SiO₂ as antireflection coating fabricated using this technique showed absorptance ~ 0.94 and emittance ~ 0.06 at 100°C after heat treatment at 500°C [Bayón et al., 2008]. Co₃O₄ based thin film coating is developed using sol-gel dip coating, showing absorptance ~ 0.84 and emittance 0.20 after thermal curing at 500°C for 30 minutes. However, thermal treatment for 4 days at 500 °C, led to enhanced absorptance ~ 0.86 together with increased emittance of ~ 0.27 [Ambrosini et al., 2011]. Ruthenium oxide thin film on gold-

coated titanium substrate showed absorptance ~ 0.91 and emittance ~ 0.16 [Morales-Ortiz et al., 2006]. K.J Cathro reported black cobalt-based structure mixed with nickel oxide or manganese oxide using dip-coating. The structures showed absorptance ~ 0.90 and emittance 0.1 at 80 °C, where emittance further increased to 0.25 at 300 °C in the case of 5% nickel containing sample [Cathro, 1984]. A tandem structure, consisting of titanium-carbon black (TiO_2/CB) and titanium-carbon nanotube (TiO_2/CNT) on SS substrates are reported as SSACs [Rincón et al., 2007]. Multilayer structures, consisting of cobalt oxide (CO) and tin oxide (TO), are fabricated on Ni coated SS substrate using this route. This optimized structure TO/CO/TO/CO/Ni/SS with absorptance of 0.808 and emittance ~ 0.045 are reported [Barrera et al., 2005]. Subasri et al. reported Ag- $\text{TiO}_2/\text{TiO}_2/\text{SiO}_2/\text{TiO}_2/\text{SiO}_2/\text{SS}$ structure using dip coating with absorptance ~ 0.94 and emittance ~ 0.13 [Subasri et al., 2016].

2.3.8.3 Paint

Spectral selective structures are also fabricated by only applying black paints on metallic substrates. Generally, paint as spectral selective coatings show higher thermal emittance. Thickness sensitive spectrally selective (TSSS) paints are suitable for low temperature solar thermal applications. The optimized TSSS paint on Al substrate is reported to have absorptance ~ 0.92 and emittance ~ 0.015 at 100 °C [Orel et al., 1991]. The two TSSS paint based commercial products, Solariselect-ZTM, and Solkote/SORB-II are from SOLEC USA [Kennedy, 2002]. Semiconductor (Si, Ge, or PbS) pigmented paint with silicon binder is explored for spectral selective applications. These structures showed good solar absorptance of ~ 0.96 , 0.91 and 0.83 for PbS, Ge and silicon pigments, respectively. However, these structures showed high thermal emittance ≥ 0.70 [Pettit and Sowell, 2002]. For higher temperature solar thermal applications, the mixture of metal oxide and ferrites based paints are developed for SSACs, showing absorptance of ~ 0.90 in low wavelength region but emittance ≥ 0.45 [Kennedy, 2002]. A cermet based paint MasterbeadR consisting of 86% alumina, 2-4 % silica, 6-8% iron oxide, and 4-5 % titania into bauxite particle using Norton process showed absorptance of ~ 0.93 . This structure also showed high thermal as well as mechanical stability up to 1000 °C [Griffin et al., 1986]. The 2500 black paint of pyromarkR series is commercially produced by Big Three Industries, showing high absorptance ~ 0.97 , together with higher emittance ~ 0.9 at 1000 °C [Kennedy, 2002].

2.4 SSAC development in chronological order

The idea of harnessing solar energy into solar thermal using spectrally selective coating was proposed by H. Tabor, J.T Gier, and R.V Dunkel in between 1955 to 1961 [Tabor, 1956, Tabor, 1961, Gier and Dunkel, 1958]. In beginning black nickel, black copper oxide and black chrome were few coatings developed for low-temperature applications on flat plate collectors. These coatings were deposited using the electrochemical route. Black nickel on Ni coated copper, black copper oxide on copper substrate, and black chrome on Ni coated Cu, and SS are reported with absorptance and emittance of 0.88-0.92 and 0.03-0.10, 0.9 and 0.1-0.2, 0.9 and 0.09, respectively [Tabor, 1956, Tabor, 1961, McDonald, 1975]. The research and development in the field of solar energy resources got attention due to the energy crisis in 1970 [Boffey, 1970], and further due to global warming, forcing the need for renewable energy sources. The various types of spectrally selective absorber coating were developed using different chemical and physical deposition routes. The developed SSAC structures are classified as Intrinsic or mass absorber, semiconductor-metal tandem structure, Multilayer absorber, Metal-dielectric composites, surface texturing, and selective solar transmitting paint or black body like absorber. Intrinsic or mass absorber showed better structural stability, but its optical performance is less effective as compared to multilayer absorber structures [Kennedy, 2002, Cao et al., 2014]. These kinds of spectral properties are shown by transition metal based oxide semiconductors. Hafnium carbide, a high melting point material with structural or compositional changes together with the anti-reflecting layer, can offer the required optical properties [Kennedy, 2002]. Semiconductor-metal tandem structures consist of the bottom metallic layer, acting as an IR

reflector, and a thin semiconductor layer as an absorber in the UV-Vis range. These SSACs are fabricated with top antireflection coating to avoid reflectance loss as semiconductors may exhibit high reflectance due its high refractive indices. B.O. Seraphin reported a Si-based SSAC using the CVD technique [Seraphin, 1976, Seraphin, 1979]. Multilayer metal and dielectric structures are another kind of SSACs, where multiple reflections at interfaces are responsible for high absorptance in the desired wavelength range. Schmidt et al. reported several multilayer absorbers consisting of metals (e.g. Mo, Ag, and Ni) and dielectrics (e.g., Al₂O₃, SiO₂, ZnS) for solar thermal applications [Schmidt et al, 1963, Schmidt and Park, 1964]. Metal-dielectric composite based SSAC structure is the most common SSAC for solar thermal applications in mid as well as high temperature range applications. These are known as CERMET coatings and efforts are continuously going on to improve their performance together with environmental and corrosion robustness. These cermet structures show better optical performance i.e. higher absorptance and lower thermal emittance. Cermet based structures may provide large flexibility in terms of materials' selection, layer thickness, constituent material particle size, shape and orientation. Various cermet based structures such as graded cermet, metal pigmented, and double cermet SSACs are reported in literature [Cao et al., 2014]. Using effective medium theory approach SSACs with desired optical properties are simulated and realized experimentally [Andersson et al., 1980]. Graded cermet and metal pigmented SSACs use the same concept of reducing reflection by gradually reducing the metal volume fraction from the bottom layer to the top layer. In double-cermet layer structures, interference plays an additional role in absorbing the radiation. Double cermet layer structures consisting of high metal volume fraction followed by low metal volume fraction on the metallic substrate are also modelled and experimentally realized with enhanced solar thermal properties. Also, an antireflection coating layer is coated further to enhance the light trapping and protection of SSAC structures [Wang et al., 2017]. The other SSACs include surface texturing [Kussmaul et al., 1992] and black paint [Orel et al., 1991]. The absorber surfaces are made rough by its proper texturing to trap the light. The surface roughness of these structures is lower or in the range of lower wavelength in the UV-Vis range. Such surfaces will absorb the incoming UV-Vis radiation by optical trapping and act like a perfect reflecting layer for higher wavelength (IR radiation) radiation. Highly doped semiconductor (SnO₂:F, SnO₂:Sb, In₂SO₃:Sn) coatings on black body like absorber is also used as SSAC [Granqvist, 1989]. Among the various reported SSACs, commercially produced SSACs are generally cermet based structure [Selvakumar and Barshilia, 2012]. This section will present the overview of so far developed different SSAC structures. Also these structures are categorised in three different types as per their thermal stability in low, middle and high temperature range. The low temperature range is less than 100°C, mid temperature range is more than 100 °C and lower than 350°C and high temperature range is greater than 350 °C.

2.4.1 Low temperature ($\leq 100^{\circ}\text{C}$) spectrally selective absorber coating structure

Generally, low temperature spectrally selective absorber structures are employed for domestic hot water applications. These kinds of coating use non-concentric type collectors such as flat plate collectors and evacuated tube collectors. One of the first spectrally selective absorber black nickel was employed for hot water application [Agnihotri and Gupta, 1981]. This structure is stable in low-temperature region. However, in an open environment condition due to presence of humidity, its optical properties start degrading around 200 °C [Wackelgard, 1998]. Black copper oxide on copper substrate coating structure was developed by Tabor et al., in 1956 and commercialized for hot water applications [Agnihotri and Gupta, 1981]. The high-temperature thermal stability of this structure is limited due to the materials' degradation and also its corrosion instability. Further thickness sensitive and thickness insensitive spectrally selective absorbers, carbon embedded dielectric nanocomposite as well as nickel composite based selective coatings are also reported for low temperature solar thermal applications. The thickness sensitive and thickness insensitive absorber surfaces generally exhibit exceptionally high thermal emittance. A novel black coloured (CuCoMnO_x) composite on aluminium substrate and nanogold containing copper selective solar absorber surfaces are also reported for

low temperature application. **Table 2.1** summarizes the development of low temperature spectrally selective absorber in chronological order.

Table 2.1 List of low temperature SSAC in chronological order

Structure	Substrate	Deposition Technique	Absorptance (α)	Emittance (ϵ)	References
Ni-ZnS alloy	SS	Electroplating	0.84	0.18	[Mcdonald and Curtis, 1976]
	Ni	Electroplating	0.96	0.007	[Borzoni, 1976]
	SS	Electrodeposition	0.91	0.1	[Lira-Cantú et al., 2005]
Black Copper (CuO)	SS	Electroplating	0.98	0.05	[Bhowmik et al., 2001]
	Cu	Conversion method	0.94	0.08	[Xiao et al., 2011]
	Cu	Chemical oxidation	> 0.95	<0.07	[Karthick Kumar et al., 2013]
TSSS	Al	Coil-coating processes	0.92	0.38	[Orel et al., 1990]
	Al	Coil-coating processes	0.92	0.15	[Orel et al., 1991]
	A	Draw bar coater	0.90-0.92	0.2-0.25	[Crnjak Orelet al., 1996]
	Al	Spray	0.90	0.20	[Kunič et al., 2011]
TISS	Metal sheet	Sol-gel	0.90	0.3	[Japelj et al., 2008]
Carbon Embedded Dielectric Matrix	Al	Sol-gel	0.71 & 0.84	0.06 & 0.04	[Katumba et al., 2008]
	Al	Sol-gel	0.85	0.05	[Roro et al., 2012]
	Al	Sol-gel	0.84	0.2	[Roro et al., 2012b]
Nickel Composite	Cu	Electrodeposition	0.94	0.08	[Tharamani and Mayanna, 2007]
	FTO glass	Electrodeposition	0.83	0.14	[Klochko et al., 2015]
CuCoMnO _x Composite	Al	Sol-gel	0.9	0.05	[Kaluža et al., 2001]
Nanogold	Cu	Solution chemical technique	0.86	0.09	[Chang et al., 2013]

2.4.2 Mid temperature spectrally selective absorber coating structure

In mid-temperature range, spectrally selective absorber coating is mainly employed for industrial process heat and desalination application. Various solar selective absorber structures have been reported, and some of them are scaled for their potential in mid-temperature range. Black chrome (BC), a cermet based structure, is one of the most common selective solar absorbers for solar thermal applications in mid-temperature range. Black chrome on Ni coated Cu was commercialized by MTI, USA. BC coated on Cu, and SS surfaces are also commercialized by Energie Solaire, Switzerland, and Chrome Coat, Denmark [Brunold et al., 2000]. BC on dull nickel modified substrate or rough surface is developed with enhanced absorption by NASA Lewis research centre [McDonald, 1975]. Alumina (Al_2O_3) based cermet structure is the second most explored selective solar absorber in this temperature range. Metal – dielectric composite structures with Ni, V, Cr, Co, Cu, Mo, Ag, Si, and W as metal in Al_2O_3 dielectric matrix are reported as selective absorber surfaces [Möller & Hönicke, 1998]. Ni pigmented nanoporous anodized alumina (Al_2O_3) based selective absorber with absorptance ~ 0.85 - 0.97 and emittance 0.08 - 0.21 has been developed and commercialized by Showa, Japan, and Tekno Term Energi, Sweden. This surface shows thermal stability in $300\text{ }^\circ\text{C}$ to $500\text{ }^\circ\text{C}$ range. Co pigmented nanoporous anodized alumina as selective surfaces are also reported with absorptance ~ 0.92 and emittance 0.28 . Further, Kumar et al., reported Ni, Co co-pigmented anodized alumina cermet structure with absorptance ~ 0.95 and emittance ~ 0.14 [Kumar & Dixit, 2019]. This structure shows better corrosion and thermal stability up to $350\text{ }^\circ\text{C}$. However, Ni pigmented SSAC structure is not suitable for CSP application due to diffusion of Al and Al substrate at higher temperatures [Kennedy, 2002]. Small particles of Ge, Si, or PbS semiconductor with Si binder painted on copper substrate showed absorptance ~ 0.91 , 0.83 , and 0.96 in the case of Ge, Si, and PBs, respectively. These surfaces, however, show very high thermal emittance up to $300\text{ }^\circ\text{C}$ [Pettit & Sowell, 1976]. TiN_xO_y cermet based absorbers on the copper substrate with SiO_2 as an anti-reflecting top layer are reported with absorptance ~ 0.94 and emittance ~ 0.08 - 0.12 [Lazarov et al., 1993, Schellinger et al., 1994]. But this structure shows degradation after exposure to open air. The surface on Al and Cu substrates showed better stability in open-air [Schellinger et al., 1994]. The absorptance ~ 0.95 and emittance ~ 0.04 values are reported for TiNO_x on Al and Cu substrates, and these coatings are commercialized by Almeco-TiNOX, Germany. A graded Ni-NiO based cermet structure with absorptance ~ 0.96 - 0.98 and emittance ~ 0.13 - 0.15 at $100\text{ }^\circ\text{C}$ is developed and commercially produced by S-Solar, Sweden. Double layer W-AlN and SS-AlN based cermet structures consist of HMVF and LMVF layers, showing enhanced optical performance, which is commercialized by TurboSun, China [Selvakumar and Barshilia, 2012]. Several other metal–dielectric composite tandems and metal–dielectric multilayer structure based SSACs have been reported. **Table 2.2** summarizes the spectrally selective absorber coatings for mid-temperature solar thermal application.

Table 2.2 List of Mid temperature SSAC in chronological order

Structure	Substrate	Deposition Technique	Absorptance (α)	Emittance (ϵ)	References
Black chrome ($\text{Cr-Cr}_2\text{O}_3$)	SS	RF sputtering	0.9	0.1	[Fan and Spura, 1977]
Ni- Al_2O_3	Al	Anodization	0.93-0.96	0.10-0.20	[Andersson et al., 1980]
Co- Al_2O_3	Al	Anodization	0.92	0.28	[Niklasson and Granqvist, 1984, Nahar et al., 1989]
		Anodization	0.92	0.16	[Cuevas et al., 2014]
Ni,Co- Al_2O_3	Al	Anodization	0.95	0.14	[Kumar and Dixit, 2019]
M-AlN	Glass	DC magnetron	0.93-0.96	0.03-0.04	[Zhang, 1998]

		sputtering			
	Glass and Cu	Plasma enhanced chemical vapor deposition (PECVD)	0.95	0.05	[Rebouta et al., 2012]
	Si	RF/DC sputtering	0.94	0.04	[Du et al., 2011]
	Quartz	Reactive DC Sputtering	0.82-0.94	0.05-0.27	[Wu et al., 2013]
	SS	Reactive DC Sputtering	0.938	0.099	[Feng et al., 2015a]
NbTiON/SiON	Cu	Magnetron Sputtering	0.95	0.07	[Liu et al., 2012]
CrN _x O _y /SiO ₂	Cu & Si	DC magnetron Sputtering	0.947	0.050	[L. Wu et al., 2013]
CrMoN/CrON	SS & Al	Sputtering	0.90-0.92	0.13-0.15	[Selvakumaret al. 2013]
	Al	Magnetron Sputtering	0.78		[Gaouyat et al., 2013]
Ultrafine Chromium Particles	KBr	Evaporation	0.97	0.19	[Granqvist & Niklasson, 1977]
Carbon-Silica Nano-composite	Glass	Sol-gel	0.94	0.15	[Katzen et al., 2005]
Cr _x O _y /Cr/Cr ₂ O ₃	Cu	Pulsed Sputtering	0.899-0.912	0.05-0.06	[Barshilia et al., 2008]
	Al	Electrochemical Process	0.923	0.06	[Ding et al., 2010]
TiN/TiSiN/SiN	SS	DC reactive Magnetron Sputtering	0.95	0.04	[Feng et al., 2015b]
MgO/Zr/MgO Multilayer	SS	e-beam evaporation	0.92	0.09	[Nuru et al., 2015]
W-SiO ₂ and Nb-TiO ₂	SS	RF/DC Sputtering	0.91/0.93	0.08/0.09	[Wäckelgård et al., 2015]

2.4.3 High temperature spectrally selective absorber coatings

The high temperature stable spectrally selective absorber coating is required for electricity generation using CSP plants. The solar thermal conversion efficiency depends on the coating material used in a spectrally selective absorber. For power generation using CSP plants, the spectrally selective absorber with high absorptance (> 95%) and low thermal emittance (<10%) is required. The coating structure must have thermal stability beyond 400 °C in the air as well as in vacuum conditions. Also, the solar absorber must be oxidation and corrosion-resistant at high temperature to avoid degradation of its optical properties and thus, solar thermal performance. At high temperatures, the thermal losses may increase drastically as the fourth power of temperature (T^4), according to the Plancks' radiation distribution [Selvakumar &

Barshilia, 2012]. Various high temperature stable spectrally selective absorber using high melting point transition metal and dielectric based composite structures have been explored and reported. The details of such high-temperature coatings are summarized in **Table 2.3**. Low refractive index dielectric, such as Al_2O_3 is mostly used in these coatings to minimize the front surface radiation losses. Additionally, Al_2O_3 offers high-temperature stability. Various metals such as Pt, Mo, W, Ni, and dielectric like Al_2O_3 based composite spectrally selective absorber structures have been reported. At high temperature, the structural and chemical composition stability of each layer is also important to prevent the solar thermal properties. The spectrally selective layers are prone to interdiffusion in case of multilayer structure, which in turn will degrade the optical properties. Also, at higher temperature ($>400\text{ }^\circ\text{C}$) interdiffusion from the substrate into absorber materials may occur and thus, degrade the solar thermal performance [Cheng et al., 2013].

Table 2.3 List of high-temperature SSAC in chronological order

SSAC structure	Substrate	Deposition Technique	Absorptance (α)	Emittance (ϵ)	References
MgO/Au	SS	RF sputtering	0.9	0.1	[Fan & Zavracky, 1976]
M- Al_2O_3 (M = Au, Ag, Cr, Cu)	Glass	Co-evaporation	0.90	0.05	[McKenzie, 1979b]
	Quartz	Co-evaporation	0.98	-	[Craighead et al., 1981]
	Cu	Co-evaporation	0.95	0.1	[Niklasson & Granqvist, 1983, 1984]
Pt – Al_2O_3	SS	RF Co-Sputtering	0.92	0.14	[Vien et al., 1985]
Co – Al_2O_3	Cu and glass	e-beam evaporation	0.90	0.024	[Zhang & Mills, 1992a, 1992b]
Mo- SiO_2 / Al_2O_3 and Pt/ Al_2O_3 Multilayer	Si, quartz, and alloys	RF sputtering	0.95 and 0.92	0.08 - 0.2 and 0.14	[Schön et al., 1994]
Al_2O_3 Cermet	Glass	Mo-evaporation	0.955	0.032	[Zhang & Mills, 1996]
Cr- Cr_2O_3 and Mo- Al_2O_3	Cu and Glass	DC Sputtering	0.88 to 0.94	0.15 - 0.04	[Teixeira et al., 2001]
Zr- ZrO_2	Glass	DC reactive sputtering	0.96	0.05	[Zhang et al., 2003]
Ti- Al_2O_3	Nickel	Ion beam sputter deposition	0.93	0.09	[Jaworske & Shumway, 2003]
Mo- SiO_2	SS and Glass	Sputtering	0.94	0.13	[Esposito et al., 2009]
HfOx/Mo/HfO ₂	SS & Cu	Magnetron Sputtering	0.902-0.917	0.15-0.17	[Selvakumar et al., 2010]
Ag – Al_2O_3	Cu, Si & Glass	Magnetron Sputtering	0.93	0.04-0.05	[Barshilia, et al., 2011]
Pt – Al_2O_3	SS	RF Sputtering	0.98	0.05	[Nuru, et al., 2012]
Mo- SiO_2	Glass	Sputtering	0.95	0.15	[Zheng et al.,

					2013]
Al _x O _y /Pt/Al _x O _y Multilayer	Cu	e-beam vacuum evaporator	0.951	0.09	[Nuru et al., 2014]
Al _x O _y -AlN _x -Al	Quartz glass	DC Magnetron Reactive Sputtering	0.94	0.07	[Yue et al., 2003]
TiAlN/TiAlON/Si ₃ N ₄	Cu	Magnetron Sputtering	0.95	0.07	[Barshilia et al., 2006]
Ti _{0.5} Al _{0.5} N/Ti _{0.25} Al _{0.75} N/ AlN	Si	RF/DC Magnetron Co- sputtering	0.945	0.04	[Du et al., 2011]
TiAlN/TiAlON/SiO ₂	Cu and glass	DC Magnetron Sputtering	0.955	0.05	[Rebouta et al., 2012]
HfMoN(H)/HfMoN(L) /HfOH/Al ₂ O ₃	SS	Magnetron Sputtering	0.94-0.95	0.13-0.14	[Selvakumar et al., 2012]
Ti/AlTiN/AlTiON/AlTi O	SS	Magnetron Sputtering	0.933	0.16-0.17	[Barshilia, 2014]
TiAlCrN/TiAlN/AlSiN	SS	Cathodic Arc	0.91	0.07	[Valletti et al., 2014]
SS- (Fe ₃ O ₄)/Mo/TiZrN/TiZ rON/SiON	SS	Reactive DC/RF Magnetron Sputtering	0.92	0.08	[Liu, et al., 2014]
Al ₂ O ₃ -W and AlSiN/AlSiON Bilayer	SS	Magnetron Sputtering	0.93-0.95	0.07-0.01	[Rebouta et al., 2015]
NbTiON/SiON	Cu	Magnetron Sputtering	0.95	0.07	[Liu et al., 2012]
Cr-Al-O	SS & Si	Cathodic Arc ion plating	0.924	0.21	[Liu et al., 2014]
AlCrNO	SS	Cathodic Arc Plating	0.93		[Gong et al., 2015]
CrAlO	SS	Cathodic Arc Ion Plating	0.918-0.924	0.154- 0.170	[Liu et al., 2015]
SS-AlN	Glass	Sputtering	0.94-0.95	0.04-0.05	[Zhang, 1998., Zhang et al., 1998]
ZnO/black ZnO	Glass	Sputtering	0.90	0.26	[Brett et al., 1986]
Mo-Si ₃ N ₄	SS & Si	Sputtering	0.926	0.017	[Céspedes et al., 2014]
Carbon Nanotube Based Selective Absorber	SS, Cu, Ni & Cr	Spray	>0.92	<0.01	[Abendroth et al., 2015]
ZrOx/ZrC-ZrN/Zr	SS, Cu	Sputtering	0.85-0.88	0.04-0.10	[Usmani & Dixit, 2016]
Al ₂ O ₃ /Si ₃ N ₄ /MoSi ₂ - Si ₃ N ₄	Inconel	Sputtering	0.87-0.92	0.1-0.2	[Rodríguez- Palomo et al., 2018]

Thus, we noticed that most of the high temperature spectrally selective absorbers are cermet based structures. These coating structures are mainly deposited using PVD (sputtering) routes. However, other deposition techniques such as spray, sol-gel, electrodeposition etc. are also used for high temperature spectrally selective coating. Though numerous high temperatures spectrally selective coatings are reported, very few of these structures are commercialized. Mo-SiO₂ and Al₂O₃/W- Al₂O₃/W cermet based SSACs are commercially produced by Angelantoni-ENEA, Italy. Mo-SiO₂ solar absorber coatings showed an absorptance of 0.94 and an emittance of 0.13 at 580 °C. This structure is reported to exhibit high thermal stability up to 580 °C in the vacuum. Al₂O₃/W- Al₂O₃/W coating showed an absorptance of 0.93 and emittance of 0.10 at 400°C and 0.14 at 550°C. Al₂O₃ based cermet coatings are reported with a high absorptance of 0.96 and low emittance of 0.10 at 400°C, Mo- Al₂O₃, and W- Al₂O₃ cermets showed absorptance of 0.96 and emittance 0.16 at 350 °C. These coating structures are commercialized by Siemens, Germany [Zhang, 2000]. Al₂O₃ cermet based structure is reported to be thermal stability up to 400°C in air. However, Mo-Al₂O₃ and W- Al₂O₃ SSACs showed thermal stability up to 350-500°C in the vacuum. Schott, a German-based company, is also producing high-temperature SSAC with an absorptance of 0.95 and emittance of 0.10 at 400°C. This structure is also showing thermal stability up to 500°C in vacuum [www.schottsolar.com/global/products/concentrated-solar-power/%0Aschott-ptr-70-receiver]

2.5 Classification of SSAC including next generation coatings

Numerous SSAC structures are reported so far. These are mainly categorized as (a) Metal dielectric based multilayer, (b) Metal- dielectric composite structure, (c) Surface texturing, and (d) Semiconductor-Metal tandem structure. Other than these common SSACs, new structures are also explored and called as the next generation SSAC structures [Kennedy, 2002]. These different SSAC structures are summarized in Fig.3, including meta-material and plasmonic-based structures as the next generation SSACs. Schmidt et al. in 1963 reported several Metal (e.g., Mo, Ag, Cu, Ni) - Dielectric (e.g., Al₂O₃, SiO₂, CeO₂, ZnS) based multilayer structures consisting alternate layer of metal and dielectric with dielectric on top, serving the anti-reflection purpose. These multilayer structures showed a potential for high-temperature applications (Kennedy et al., 2002). Another SSAC structure is metal-dielectric composite structure, which is deposited on metal or IR reflecting layer coated metallic substrate. Black chrome (Cr-Cr₂O₃) is one of the most common SSAC structure fall in this category. SSAC structures using surface texturing are also reported [Kusmaul et al., 1992]. Textured surfaces are niddle-like or nanoporous structures. Here, the properly aligned structures towards the incoming solar radiation may increase the solar absorptance. Semiconductor- metal tandem structure with antireflection coating on top is another important SSAC structure [Seraphin, 1976]. The low bandgap semiconductor, e.g., Si, Ge, and Pb are the best suitable for this type of absorber structures. Here, metallic substrates act as IR reflector and antireflection coating on top minimizes the high reflection of semiconductor in the UV range. Few materials with intrinsic properties of solar absorptance have been observed [Kennedy et al., 2002]. However, due to the shortage of naturally occurring and the limited spectral selectivity, intrinsic or mass absorbers are not widely explored. Nowadays, Meta-material/Plasmonics based solar selective coatings are getting attention because of their wider spectral selectivity and high absorptance. Meta-materials are periodic metallic micro or nanostructures fabricated on dielectric spacer coated on metallic substrates [Blanco et al., 1996, Wang et al., 2015]. Basically, here using proper surface modifications, the interaction of light with matter is increased, which in turn results in enhanced solar absorptance. It has been reported that these structures can be developed for the high-temperature applications using high-temperature melting point metal [Han et al., 2016]. Currently, meta-materials or plasmonic-based SSAC structures are being investigated at lab scale only, and there is a need for exploring such coatings for various applications.

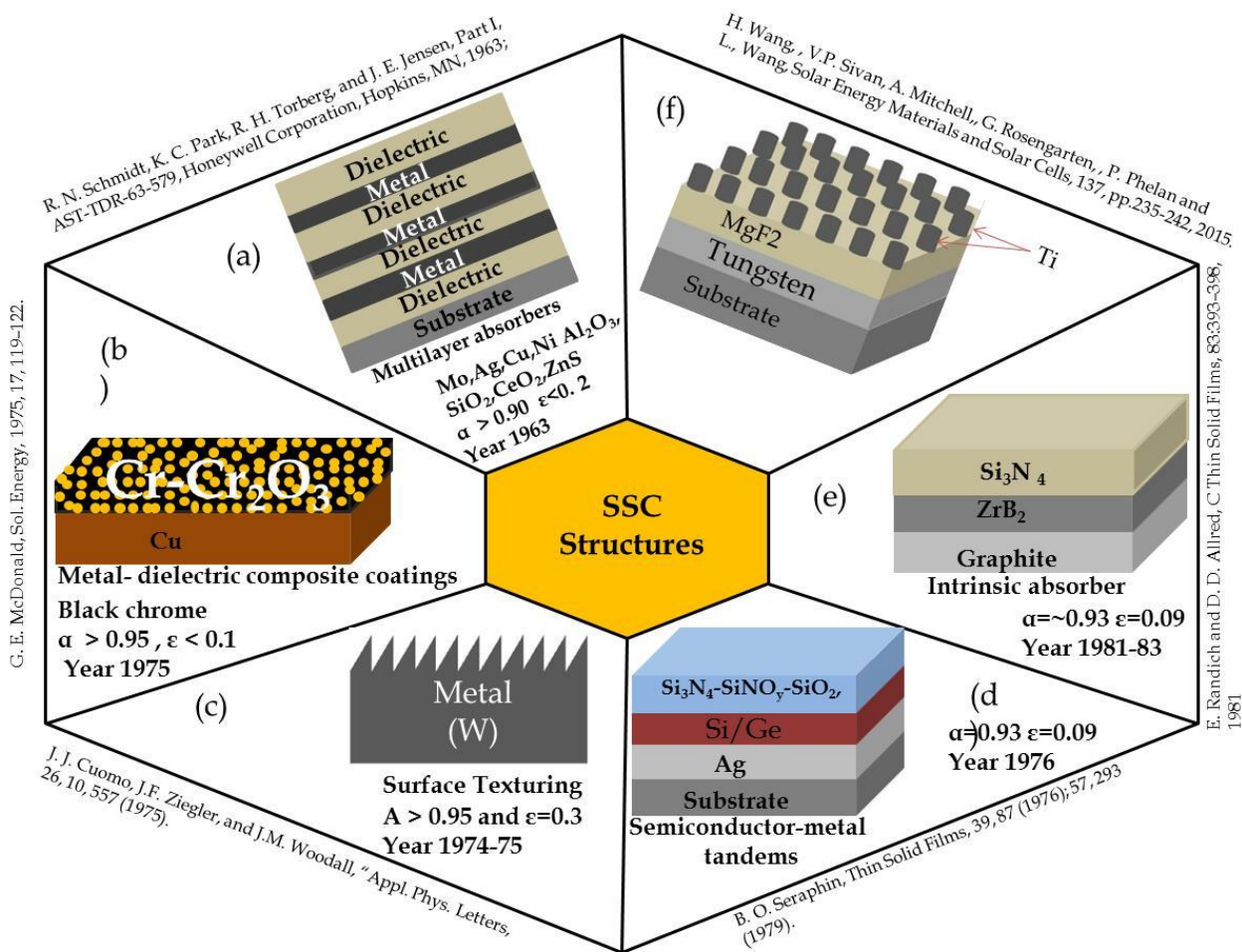


Figure 2.3 Schematic of different spectrally selective absorber coatings

2.6 Issue and challenge in development of SSAC

Since 1955-56, various spectrally selective coatings are designed and developed using different solution routes (Electrochemical, chemical conversion sol-gel, spray pyrolysis, paint), PVD (sputtering) as well as CVD routes. Initial SSACs were fabricated using the electrochemical route, and also some of them were scaled and commercially produced. Black chrome was one of the first SSAC fabricated and later commercially produced [Brunold et al., 2000]. The solution route involves simple fabrication steps and may work at lower operating temperatures. However, solution route has several disadvantages, such as the requirement of large chemical precursors, which may lead to environmental toxicity [Kennedy et al., 2002, Cao et al., 2014]. Also, these solution route based structures are mostly applicable in low-temperature range. At higher temperatures, these structures face problems in terms of their chemical and thermal stability. Thus, even though several SSAC structures were reported using the solution route at lab scale, very few were realized for scaling up to use in real solar thermal applications. As an alternative, vacuum-based techniques are explored. The majority of the SSACs fabricated using PVD (e.g. sputtering). These techniques require low material consumption and generate negligible environmental pollution. Vacuum based fabricated structures show good reproducibility. PVD coated structures show better adhesion as well as structural and chemical stability even at higher temperatures. Also, using PVD route, various structures can be fabricated easily as compared to solution route. PVD technique is not hazardous for the environment [Selvakumar & Barshilia, 2012]. This process requires very low pressure of the order of 10^{-6} mbar (in case of sputtering), which makes this complex and costly. Thus, even after various SSAC structures reported at lab scale, very few SSAC structures are being produced

commercially because of inherent system complexities for scaling towards larger surface areas [Kennedy et al., 2002, Selvakumar & Barshilia, 2012]. At low temperature, the solar thermal applications are well established and used in various applications such as domestic hot water supply, industrial heat process, space heating, and cooling applications. However, at higher temperatures, there are numerous inherent difficulties, including the thermal losses in high temperature solar thermal systems. Out of so far reported SSAC structures, very few are stable at higher temperatures in vacuum only. These structures should exhibit thermal as well as structural stability at a higher temperature in open-air environmental conditions [Kennedy, 2008]. In the case of vacuum break, these structures, need to be stable. So far, none of the coatings is available for higher temperature solar thermal applications under open-air conditions.

2.7 Summary

The solar thermal technology possesses enormous potential to fulfill the global energy demand with minimum or negligible environmental pollution. The demand for spectrally selective absorber coatings is increasing for high temperature solar thermal systems. The spectrally selective absorber coating is employed on absorber of the receiver tube for converting incident solar energy into thermal energy, which can be used to meet the energy requirement for various applications ranging from low to high temperatures. The efficiency and cost of solar thermal energy conversion system depend upon it. In this chapter, the concept of solar radiation and its availability on earth's surface has been presented. The development of spectrally selective absorber coating has been discussed in chronological order for low, middle, and high-temperature range. The different kinds of conventional SSAC structures, together with next-generation absorber coatings, are presented. Further, the associated issues and challenges in the development of SSACs are discussed in detail. Numerous selective absorber coatings have been reported for low, mid, and high temperature solar thermal applications. These are mostly cermet based structures.

Most of the SSACs are fabricated using physical vapour deposition route. The requirement of low-temperature stable SSAC is limited. However, the requirement for mid and high-temperature stable SSACs is continuously increasing to improve the overall efficiencies of solar thermal systems. Notably, high-temperature stable coatings are very important for efficient CSP plants. In mid-temperature range, few SSACs are commercially available. However, in high-temperature range very few or say two-three SSACs are scaled and commercially produced. These structures are thermally stable in only vacuum. Further, the commercially available SSACs are fabricated using sputtering system, which is a complex and also not cost-effective technique compared to the solution route. Thus, there is requirement for developing new SSACs using easy and cost-effective techniques. Also, there is a need to develop SSACs, which can be thermally stable in high-temperature under open ambient conditions. The high-temperature stable transition metal and dielectric composites, together with suitable antireflection layer, may offer great potential in developing high temperature stable spectrally selective absorber coatings.

