Electronic Applications of Styrene–Butadiene Rubber and Its Composites

Ranimol Stephen and Sabu Thomas

Abstract Stretchable materials in electronics industry have attracted tremendous interest because it can maintain high strain. Therefore, soft materials find application in electromagnetic interference (EMI) shielding, piezoelectric materials, actuators, pressure sensors, capacitive sensors and energy storage devices and solar cells. This chapter provides an outlook into the electrical properties and electronic applications of styrene–butadiene rubber (SBR) composites in the presence of various types of conducting fillers.

Keywords SBR composites · Conducting fillers · Electronic applications

1 Introduction

Conductive rubber composites have received great interest over the last decade from various scientific fields as their applications in electromagnetic shielding, flexible electronic devices, thin film transistors, electrodes and sensors are almost indispensible [1–4]. The possibilities and applications of stretchable and flexible materials in the manufacture of electronic devices is tremendous. However, the basic characteristic properties of both natural and synthetic rubbers are its remarkable electrical resistance, elasticity, toughness, impermeability and adhesiveness which makes it a useful material in different fields rather than in electronics industry. Electrical properties in rubber can be achieved only by the formation of

---

R. Stephen (✉)
Department of Chemistry, St. Joseph's College (Autonomous), Devagiri, Calicut 673 008,
Kerala, India
e-mail: ranistephen@gmail.com; ranistephen@yahoo.com

S. Thomas
International and Inter University Center for Nanoscience and
Nanotechnology, School of Chemical Sciences, Mahatma Gandhi University,
Priyadarshini Hills P.O., Kottayam 686 560, Kerala, India
e-mail: sabuchathukulam@yahoo.co.uk

© Springer International Publishing Switzerland 2016

D. Ponnamma et al. (eds.), *Flexible and Stretchable Electronic Composites*,
Springer Series on Polymer and Composite Materials,
DOI 10.1007/978-3-319-23663-6_9

conductive networks in the matrix, which offers an electrical pathway for the conduction of electrons. It is proved that the conducting fillers (CFs) such as carbon black, nanotubes, graphene and metal particles can create an electrical pathway by the formation of filler–filler networks within the rubber matrix.

Styrene–butadiene rubber (SBR) is a synthetic rubber, also known as Buna-S, used in various sectors such as tyre, medical, footwear and automobile industries. It is produced by the copolymerization of butadiene, $CH_2{=}CH{-}CH{=}CH_2$ (75 %), and styrene, $C_6H_5{-}CH{=}CH_2$ (25 %). Pure gum strength of this non-stereospecific, amorphous polymer is low when compared to stereospecific natural rubber (NR). Subsequently, SBR will not crystallize upon stretching. However, white and black fillers-reinforced SBR exhibit excellent strength and abrasion resistance. It is resistant to mineral oils and fats, and solvents such as aliphatic, aromatic and chlorinated hydrocarbons [5].

The primary goal of this chapter is to give an outlook into the properties of SBR and various CF composites and its challenges and potential applications in electronic devices and sensors.

2 Relevance of Stretchable Materials in Electronics

Stretchable and flexible electronic composites are considered to be a revolutionary technology for both academicians and industrialists. Conductive stretchable materials have been a research theme for a long time. However, the recent developments in the fabrication of stretchable electronic materials are remarkable which mainly focused on electronic devices and sensors from elastomeric materials. Very recently, Zhu and co-workers [6] and Huang and co-workers [7] reviewed the applications of stretchable materials for flexible electronics. The main advantage of stretchable electronics is the designing of flexible, light-weight, cost-effective materials, since the matrix material is highly inexpensive compared to conventional substrates. Moreover, the key attraction of flexible electronics is its ability to bent, fold, twist and even form into different shapes without affecting the performance and properties. Flexible electronic devices are more relevant in the manufacture of medical devices for diagnosis and treatment purposes in human bodies. The potential applications include the fabrication of smart clothing, foldable displays, robotic skins, stretchable solar cells and bioinspired devices [8–10].

3 Conductive Styrene–Butadiene Rubber (SBR) Composites

SBR is an insulator, which makes it conductive by incorporating conductive materials such as metals, carbon-based fillers and ceramics. Common conductive fillers used in elastomers include conductive carbon black, carbon nanotubes (CNTs), graphite, graphite fibres, metal particles, metal wires and powders [11–18]. Conductivity of rubber matrix can be enhanced by changing the weight percentage of these conductive fillers, and it is noteworthy that not only the conductivity but physical properties can also be modified. Rubber composites are used for various applications instead of pure rubber, in which fillers act as reinforcing agents irrespective of their conducting or non-conducting nature. Till date, the actual mechanism involved in the reinforcement of filled rubber is not fully explained, but interpreted in terms of the formation of rubber–filler networks. The inclusion of rigid filler in the soft rubber matrix restricts the segmental mobility of the polymer chain. Conductivity of SBR can be varied over a wide range by varying the CF and its dispersion in the matrix.

Properties of composites depend on several factors such as the nature of individual components, size and shape of fillers, morphology of the system and nature of the interface between the phases. Interface interaction between phases plays an important role in the strength of composite in addition to ensuring uniform dispersion of filler in the rubber matrix. In the manufacturing of rubber nanocomposites, to attain the fine dispersion of filler in the matrix is still a challenging problem for the material scientists. Various methods for the fabrication of SBR composite include solution mixing, latex route, melt compounding and two-roll mill mixing. Structure and morphology of the manufactured rubber composites can be explored using different techniques such as X-ray diffraction (XRD), solid-state nuclear magnetic resonance (NMR), Fourier transform infrared (FTIR), scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

3.1 SBR/Metal, Metal Oxides and Ceramics

Conductive SBR composites are frequently manufactured by incorporating metal fillers such as copper, steel, silver, gold and aluminium. These are generally used in the form of powders or flakes. Ceramic files are also used for the fabrication of conductive composite, which includes silicon carbide, boron nitride, aluminium nitride and alumina.

Negri and co-workers [19] have synthesized magnetic nanoparticles, Fe_3O_4 (magnetite) with average size less than 10 nm to ensure better superparamagnetism to avoid large irreversible magnetic effects. These magnetite particles are then covered with conducting Ag^o to generate microparticles of Fe_3O_4@Ag, which exhibits both magnetic and conductive properties. During the preparation of SBR-DEG-Fe_3O_4 films, the formation of pseudo-chains (needles) of inorganic materials is magnetically aligned and is evident in the morphological analysis presented in Fig. 1. Magnetically aligned needle like Fe_3O_4@Ag can be clearly seen in the optical and SEM images. In the centre, the needles are normal to the surface; however, at the edge, it is diagonal to the surface due to the uniformity of the magnetic field in the centre and not in the edges. They have investigated the magneto- and piezoresistivity of nanostructured composite films based on SBR

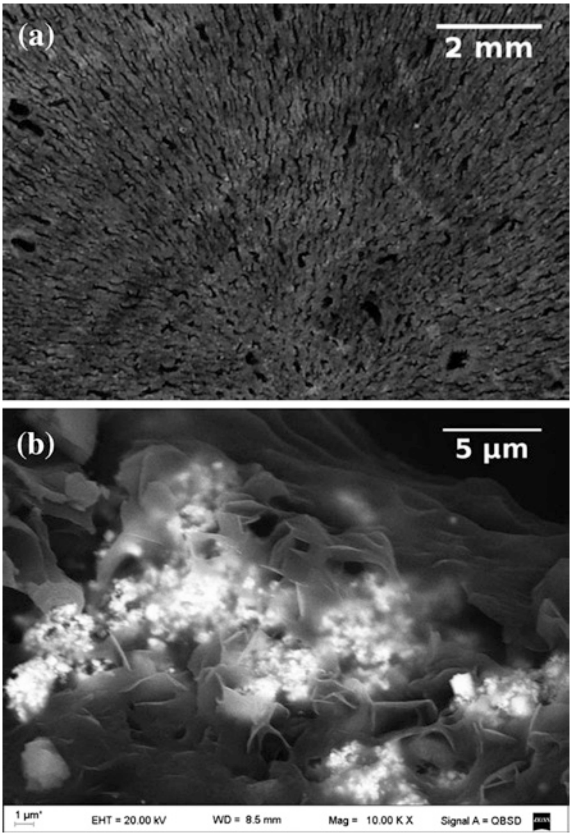

Fig. 1 SBR-DEG—12 % Fe_3O_4@Ag composite films. **a** Optical photograph and **b** SEM image [19]. Copyright 2013. Reprinted with permission from Elsevier Ltd.

filled with electrically CF. Diethylene glycol is added to SBR to get considerable electrical conductivity. The formation of structured SBR-DEG-Fe_3O_4 films with anisotropic properties is the reason behind the conductivity, which decreases the percolation critical point to observe conductivity. These films offer piezoresistive and magneto-resistive properties. Negri and co-workers [19, 20] used Fe_3O_4@Ag filler in various elastomeric matrix due to its simultaneous exhibition of magnetic and electrical properties.

Lee et al. [21] fabricated highly stretchable Ag nanowire–Ag nanoparticles (AgNW–AgNP)-reinforced electrically conductive styrene–butadiene–styrene (SBS) fibre by wet-spinning method and iterative process for Ag precursor absorption and reduction. During stretching AgNW-embedded SBS exhibits high initial electrical conductivity due to the presence of highly conductive fillers. According to them, AgNWs form bridges between AgNPs for electrical conductivity, which will retain up to 100 % strain after that decline of conductivity observed due to the breakdown of networks. SBS–AgNW composite fibre shows strain-sensing behaviour and is incorporated into a smart glove to perceive human motions is shown in Fig. 2.

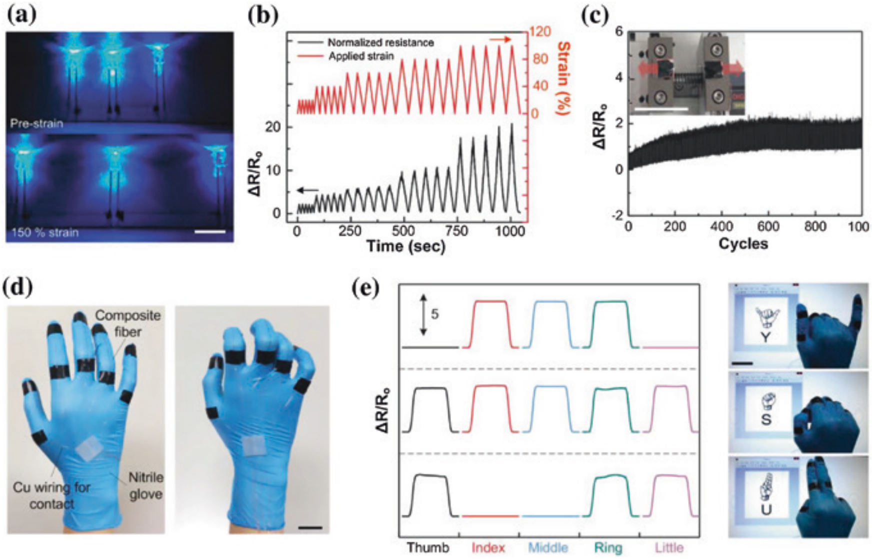

Fig. 2 **a** Images of *blue*-coloured LEDs connected by 0.56 wt% AgNW–AgNP embedded composite fibres. **b** The normalized resistance changes varying the applied strains at 0, 20, 40, 60, 80 and 100 %. **c** Reliability test measured the changes in the normalized resistance of the composite fibre during the stretching and releasing cycle. **d** Photograph of the smart glove attached to the composite fibre on each finger. **e** Motion detection of English letters '*Y*', '*S*' and '*U*' for utilizing sign language glove and photographs of detecting each letter [21]. Copyright 2015. Reprinted with permission from John Wiley & Sons

Titanium carbide (TiC) belongs to the class of interstitial carbides, in which the metal retains its closed packed lattice structure and C atoms occupy the octahedral interstices. TiC is extremely hard refractory materials and good conductors of electricity. Electrical and electromagnetic wave shielding properties of TiC-loaded SBR have been investigated by Sung and El-Tantawy [22]. According to them, SBR–TiC composite is a promising material for applications in self-electrical heating, temperature sensor, time delay switching and electromagnetic wave shielding effectiveness. The electromagnetic wave shielding effectiveness of the composite is due to reflection loss, consisting of the reflections from the material boundaries and surroundings. Reflection loss depends on the electrical conductivity and network structure of the conductive particles in the elastomer.

Measurement of electrical conductivity of filled elastomers gives information about the dispersion of filler in the matrix. Gwaily et al. [23] studied the effect of γ-radiation in the conductivity of Fe and Cu metal particles-filled SBR. In the report, they mentioned that without irradiation, the filled SBR behaves like an insulator, and conductivity, σ is in the range $10^{-12}\ \Omega^{-1}\ \mathrm{cm}^{-1}$. It is due to the weak interfacial interaction of metal–polymer and segregation of filler particles after moulding. Upon γ-irradiation >300 kGy, σ increases significantly due to the formation of filler–filler networks.

3.2 SBR/Carbonaceous Materials

Conducting SBR composites can be prepared by incorporating conducting carbonaceous fillers such as carbon black, carbon fibre, graphite and CNTs. Improvement in mechanical, thermal and electrical properties of composite is strongly influenced by the nature of filler, size, shape, surface area, surface chemistry, distribution within the matrix and processing techniques.

3.2.1 SBR/Carbon Black

Carbon black is one of the major reinforcing filler used in rubber compounds, especially in tyres to impart improved strength and performance. CB is also used as CF for the preparation of conducting elastomeric composite due to its low cost, good processability, availability and corrosion resistant [16, 24, 25]. Electrical properties of conducting carbon black have been used in antistatic, electromagnetic interference (EMI), electroactive pressure sensors and actuators. A special type of highly conductive novel carbon black with superhigh surface area and structure has been synthesized and incorporated in elastomeric matrix, which shows conductivity higher than that of conventional electroconductive carbon [26]. SBR filled with carbon black shows more network chains due to its strong absorbability [27], which thereby reduce the agglomeration of fillers and enhance the conductivity of elastomers. Conductivity of CB depends on three major factors: particle size, structure and surface chemistry. Fillers with high surface area and porosity provide high electrical conductivity to the elastomeric matrix [28]. Podhradska et al. [29] reported on the stability of electrical conductivity during cyclic thermal treatment of SBR/carbon black composites. They observed that the conductivity of SBR/CB composite increased from 1.1×10^{-2} to 3.0×10^{-2} Scm^{-1} when the temperature increased to 85 °C.

Designing of elastomeric materials with conductivity and the maintenance of mechanical performance is a challenging problem for the material scientists. The reason behind this is due to the fact that the lowering of percolation threshold concentration (PTC) is essential for better mechanical properties and good processability. Therefore, filler–filler and polymer–filler network formation is required to obtain elastomeric composite with lower PTC and higher mechanical properties. Due to the high structure of carbon black, the PTC observed is around 5–10 vol.% for conducting rubber composite system [30]. Kawazoe and Ishida [31] proposed a novel mechanism for the network formation of carbon black in an immiscible SBR/NBR blend system. They have demonstrated that the PTC of the conductive rubber composite of binary immiscible blends of SBR/NBR could change by changing the solvent. PTC reduced from 5.7 vol.% for SBR and 8.9 vol.% for NBR to 1.2 vol.% for SBR/NBR (90/10) system. In blend systems, the affinity towards CB is different for individual components, which results in the selective adsorption of filler particles on the polymer matrix. Non-uniform distribution of CB in rubber blend can be explained in terms of the molecular confinement mechanism. PTC can be controlled by the selective adsorption of CB; it reduces the aggregation of filler particles and thus localizing at the interface [32–37]. As the specific surface area of CB increases, PTC is found to be lower. Each CB differs in their electrical conductivity due to the difference in specific surface area as well as PTC. Meissner and co-workers [38] relate the effect of CB concentration and type on the electrical conductivity of SBR composite. Four different grades of CB, ISAF, HAF, FEF and La were used and found that the PTC decreases with increase in specific surface area of filler. They have theoretically correlated the conductivity of composites in terms of percolation theory. Percolation theory predicts the relation between the conductivity of composite, σ, and the volume fraction of filler, X. The equation is,

$$\sigma = \sigma_0 (X - X_c)^s \tag{1}$$

where σ_0 is the conductivity of filler particles, X_c is the volume fraction of the filler at percolation threshold and s is the quantity determining the power of the conductivity increasing above X_c. Unexpectedly, high values of s were found for SBR/CB composite and can be described by the behaviour of a single tunnel junction.

Silica-based fillers, fumed or precipitated silica, are used as reinforcing fillers in tyre industry (green tyres) because they provide better fuel efficiency and low rolling loss when compared to carbon black-filled tyres. Zhao and Wang [39] investigated the antistatic characteristics of solution-polymerized SBR composites filled with hybrid SiO_2/CB. In SSBR/SiO_2 composite, the static accumulation is found to be high, while in the presence of SiO_2/CB in SSBR composite it exhibits antistatic property. This can be attributed in terms of the antistatic nature of CB. According to their studies, the ratio of SiO_2/CB in 35/35 was the percolation threshold of the antistatic property, as the amount of SiO_2 increases the surface and volume resistivity of the composite increases.

He et al. [40] used water-soluble SBR–sodium carboxy methyl cellulose (CMC) mixture as a binder for sulphur cathode, which consists of 60 wt% insulating S active material and 40 wt% conducting carbon black filler. A remarkable change in cyclic performance of sulphur cathode was observed in the presence of SBR-CMC binder than conventional poly (vinylidene fluoride) (PVDF) binder. Binder acts as both adhesion agent and dispersing agent as it accelerates the uniform dispersion of conducting CB and insulating sulphur to ensure a good electrical contact. Capacity of SBR-CMC cathode was found to be 580 $mAhg^{-1}$ after 60 cycles, while that of PVDF cathode is 370 $mAhg^{-1}$.

3.2.2 SBR/Carbon Nanotubes (CNTs)

CNTs have high electrical conductivity along the tube axis. The percolation threshold of polymer/CNT composites is found to be considerably lower when compared to other conventional composites. Therefore, CNTs are considered as one of the ideal conducting material for elastomers. Also, its unique properties such as high mechanical strength, aspect ratio, tubular structure and nanoscale diameter make it a versatile material for the fabrication of stretchable conductive elastomeric matrix. Significant electrical properties of composites of CNTs favour their potential applications in electrostatic dissipation, EMI shielding, super capacitors, chemical sensors and automotive and aviation industries. On incorporating CNTs in elastomers, a continuous network of filler is formed across the matrix and enables the material to a sudden transition from an insulator to a conductor.

The poor dispersion of CNTs in the polymer matrix is one of the challenging problems for material scientists. In order to overcome this facet, Paul and co-workers [41] prepared masterbatches of oxidized MWCNT with SBR using two methods, one by coagulation with acetone and another by aqueous coagulation method followed by mastication in a twin screw extruder, and then analysed the masterbatch rheology to get an insight into the good dispersion and conformation of the MWCNT in the final product. Electrical resistivity decreases with increase in the concentration of MWCNT; however, the change is much less than that expected for percolation networks [42–45]. The tubes are not actually touching each other, but the decrease in resistivity can be explained by electron hopping [46].

Li and Shimizu [47] fabricated a thermoplastic elastomer based on poly(styrene-b-(ethylene-co-butylene)-b-styrene) (SEBS) triblock copolymer and multiwalled carbon nanotubes (MWCNTs) using high-shear processing technique with a screw rotation speed of 1000 rpm. Nanocomposites with 15 wt% of MWCNT show excellent electrical conductivity and stability upon uniaxial deformation with a strain less than 50 %.

Another important factor for determining the electrical properties of composites is the processing method. Nogueira and co-workers [48] reported the electrical conductivity of composites based on MWCNT and styrene–butadiene–styrene block copolymer processed by two methods: melt mixing (extrusion) and solution casting. Composites prepared by solution casting showed higher electrical conductivity than melt mixing. SBS/MWCNT with 6 wt% prepared by melt mixing and the one with 1 wt% prepared by solution casting show the same magnitude of conductivity. Lower PTC is observed for the samples prepared by solution casting method. The reason behind the decrease in electrical conductivity of extruded sample is the decrease in aspect ratio of MWCNT on applying shearing force.

In order to prevent the breaking of CNTs during processing, a novel mixing method rotation–revolution mixer was employed for the preparation of SBR/CNT composite [49]. The obtained results indicated that the new mixing technique reduced the amount of CNT required to provide high electrical conductivity to the SBR matrix than conventional processing methods.

Materials such as CNTs and FG have high aspect ratio, which enable both electrical and mechanical percolation at low filler concentration. Heinrich and co-workers [50] prepared solution styrene–butadiene rubber (S-SBR) composite using graphene nanoplates (GnPs), expanded graphite (EG), MWCNTs and a combination of EG with MWCNT. To get an insight into the specific dispersion and reinforcement of the fillers, they compared the mechanical and electrical

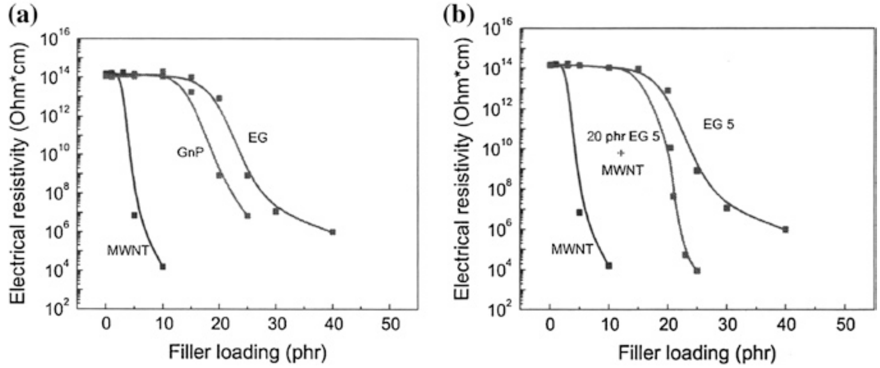

Fig. 3 Percolation of S-SBR filled with **a** GnP, EG, MWCNT and **b** 20 phr EG and various amount of MWCNT [50]. Copyright 2012. Reprinted with permission from Elsevier Ltd.

properties, presented in Fig. 3a. A remarkable drop in resistivity was observed for MWCNT composite at 3 wt%. This is attributed to the high aspect ratio of MWCNT, leading to the formation of filler–filler network. At higher concentration of EG and GnP, particles form networks, resulting in a conducting pathway and the resistivity of the matrix decreased. Mixed filler system exhibits a synergistic effect in the electrical resistivity of composites, shown in Fig. 3b.

Challenges in the design and fabrication of conducting elastomers are the homogeneous dispersion of CFs in the matrix. Graphene sheets have a tendency for restacking in the matrix, and CNTS forms entanglements. These challenges have been addressed by many researchers by using hybrid fillers in elastomers. For example, graphene and MWCNT hybrid fillers, in which MWCNT helps to form bridges between graphene platelets, provide more interface area between the filler and matrix [50, 51].

3.2.3 SBR/Graphene (GN)

Recently, graphene has attracted much attention of material scientists due to the similarities in properties to carbon nanotubes. The production of carbon nanotubes is highly expensive, so material scientists thought about an alternative and cost-effective material for potential applications. Apart from the above reason, graphene is preferred over other fillers due to high surface area, aspect ratio, mechanical properties, thermal and electrical conductivity, EMI shielding ability, flexibility and transparency [52–55]. Graphene is a single carbon layer of graphite. It is a two-dimensional one-atom-thick sp^2-bonded carbon atom densely packed like a honeycomb crystal lattice [56]. In 2010, Andre Geim and Konstantin Novoselov won the Nobel Prize in Physics for their outstanding work in graphene. In 2004, they have identified single layers of graphene and other 2-D crystals [57]. Recently, many researchers reviewed the advances in the properties of graphene-based polymer composites [58–62].

Graphene and functionalized graphene (FG) are extensively used in elastomers as a reinforcing and conducting material [63]. It is a semiconductor with a zero gap and is different from conventional Si semiconductor. Graphene sheets impart percolated pathways for the conduction of electrons in insulators like other CFs such as carbon black, carbon nanotubes and carbon nanofibres. However, the advantage of graphene is its property to enable the insulator to be a conductor at a lower PTC when compared to the PTC of other fillers [64]. It is accounted in terms of the disc-like structure of graphene and can percolate easily in the polymer matrix than rod-like CNTs. Graphene is considered to be a promising candidate to replace Si in microchip electronics and in faster-switching transistor. Modified graphenes can also be used for the fabrication of materials for potential applications by enhancing the interfacial interaction between filler and matrix. Properties of alkylamine (oleylamine and octadecylamine)-modified graphene oxide (GO)–SBR composite were found to be improved significantly [65]. SBR/graphene nanocomposite fabricated by latex compounding method attains antistatic criterion (10^{-6} S/m) at a GN loading of 3 phr, and when the loading is 7 phr, it becomes a good electrical conductor, shown in Fig. 4 [66]. Graphite flakes are converted into graphene oxide (GO) by Hummer's method [67].

Mulhaupt and co-workers [68] reported about the properties of FG and other carbonaceous materials-incorporated SBR nanocomposites prepared by aqueous dispersion blending. They have compared the performance of thermally reduced graphite oxide (TRGO), chemically reduced graphite oxide (CRGO) with that of multilayered graphene, conventional graphite carbon black and CNTs. TRGO-reinforced SBR showed improved mechanical properties and electrical conductivity when compared to other systems. Elastomers show significant improvement in mechanical, electrical and low gas permeability with functionalized graphene sheets (FGS) owing to its high aspect ratio and carbon-based structure [69, 70]. The volume resistivity of SBR (3.43×10^{15} Ω cm) reduced dramatically when compounding with electrically conducting graphene (6000 S/cm) at a vol.% of 16.5 [71].

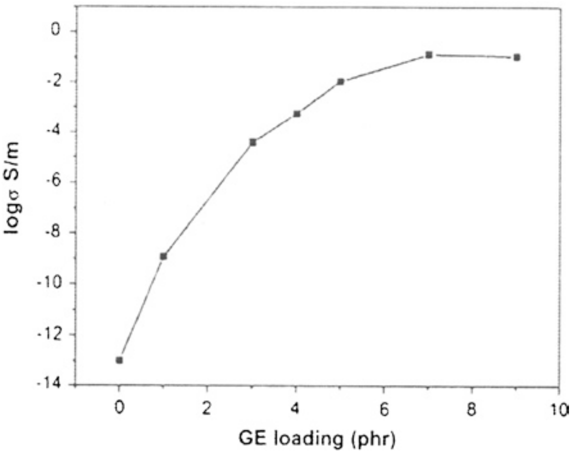

Fig. 4 Electrical conductivity of GE/SBR nanocomposites as a function of GE loading [66]. Copyright 2014. Reprinted with permission from Elsevier Ltd.

Uniform dispersion of graphene in elastomeric matrix is still a challenge. In order to overcome this, hybrid fillers of CB-reduced graphene (RG) were prepared and blended with SBR. Agglomerated CB get adsorbed on the surface of graphene to form microstructured hybrid filler. The role of CB is to block the restacking of RG sheets even after drying. When compared to SBR/RG and SBR/CB, the SBR/CB-RG showed significant improvement in mechanical properties and reduction volume resistivity due to the strong interfacial interaction between RG and SBR [72].

4 Electronic Applications of SBR Composites

Structured elastomer composite with anisotropic physical properties can be used in flexible electronics and in electronic devices. Addition of CFs makes ‘Conductive Rubber’, which can reduce or eliminate EMI and radio frequency interference (RFI) associated with stereo systems. Depending upon the intended environment and application, one can fine tune the properties of final product by varying the filler. Higher level of shielding could be achieved with the use of highly CF. Conductive elastomers can find applications in military and various industries such as telecom, medical devices and computing. Electrically conductive graphene-based SBR can be used for the manufacture of flexible electronic devices, thin film transistors, electrodes and sensors. In the near future, graphene oxide will be used for the manufacture of stretchable and electrically conductive fabrics by incorporating in elastomers [73].

The electron transport in elastomers can be explained in terms of quantum mechanical tunnelling and percolation theory [74]. If the distance between two conductive particles is large compared to atomic dimension, then the bulk resistivity of insulator predominates. However, if the distance is in the nanometre range <100 A^{o}, electrons can tunnel quantum mechanically between conductive fillers, resulting in less resistivity from the insulator than expected. At lower concentration of filler, electron transport is taking place by quantum mechanical tunnelling. As the filler concentration increases, the CFs come into contact with each other to form more filler–filler networks, leading to increase in conducting pathways. At a particular concentration of filler, the resistivity of the matrix drops dramatically and is called the PTC. Elastomeric composites exhibiting magneto-piezoresistivity find potential applications in sensors, flexible devices and electronic connectors [75–81].

4.1 *Electromagnetic Interference (EMI) Shielding*

A major concern in electronic industry is the increasing EMI among devices. Therefore, EMI shielding is essential at least for the frequency ranges

50–60 Hz in stereo systems and for 1–100 GHz in strategic applications. Electromagnetic shielding reduces the coupling of radio waves and electromagnetic and electrostatic fields by hindering the field by conducting or magnetic materials. EMI shielding used to protect the electronic devices from radio frequency electromagnetic radiation is also called radio frequency (RF) shielding. Metals such as copper, nickel or aluminium are extensively used for the EMI shielding. Although metals are very effective for EMI shielding, certain factors such as high weight, less corrosion resistance and difficulty in processing lead to the fabrication of rubber composite materials, which can substitute metals in this particular application. Insulating polymers can be converted into conducting or semiconducting polymer composite by the incorporation of CFs. Such materials find application for EMI shielding, microwave absorption and replacing conventional metals [82]. It is essential for medical and laboratory equipments to avoid the interference of other signals. Conductive SBR composite can find application as EMI and RF shielding materials in various electronic equipments.

4.2 Piezoelectric Materials

Conductive SBR composite is coming under the category ‘Flexible and Stretchable’ materials for electronic applications. Piezoelectricity means the accumulation of electrical charge on a certain material on applying a physical stress. As discussed earlier, CFs-reinforced SBR composite becomes a piezoelectric material upon stretching [19]. Piezoelectric behaviour is considered as a reversible process, in the presence of a mechanical strain charge accumulates, similarly, in the presence of an external electric field mechanical strain occurs and charge accumulates. The gripping performance of a tyre can be improved by the incorporation of piezoelectric materials [81]. Due to the flexible nature, rubber materials can generate more energy in response to a mechanical strain. Rubber composite materials can capture energy from movement or any kind of mechanical stress four times higher than the currently available piezoelectric materials. This generated energy could be used for the charging of portable electronic devices such as mobile phone. This technique can be made use of in the charging of medical devices used inside the body (pace maker). The body movements itself can generate enough power to charge the device. Another important area which will find application of flexible piezoelectric materials is shoe soles of soldiers as a source for power. Thin films of piezoelectric materials-incorporated rubber can harness tremendous amount of energy by human body movements; therefore, ‘piezo-rubber’ can find tremendous application in the near future.

4.3 Other Applications

Rubbery materials can be used for the manufacture of medical devices for diagnostic and treatment purposes due to its bendable, curved and stretchable nature. In addition to the above-mentioned applications, SBR composites with CFs are being explored for the manufacture of LEDs, sensors, actuators, smart clothes, artificial muscles, foldable displays, robotic skin (touch sensor) and solar cells. Elastomer-like electrode is fabricated by blending of conductive polyaniline (PANI) and a soft triblock copolymer poly(styrene-co-ethylene-co-styrene) grafted with maleic anhydride (SEBS-g-MA) to be used for artificial muscles [82]. Soft materials are required for smart applications that are to accommodate large actuation strains without increasing the stiffness of the material. Here, SEBS is used to control the stiffness of the material and endow flexibility and stretchability to the material.

5 Concluding Remarks

Stretchable electronics is considered to be a fast-growing revolutionary technology. From the stiff and rigid electronic devices to bendable, curved, twisted and stretchable devices represent the progress in electronic technologies. SBR composites with CFs will benefit significantly in tyre and automobile industries and in the manufacture of medical devices, shoe soles, artificial electrodes and sensors as it can sustain large strain. By incorporating conductive fillers, not only the electrical properties but also the mechanical properties of the matrix get improved. However, one of the biggest challenging problem in the fabrication of rubber composites is the formation of uniform dispersion of filler particles in the matrix. The development of advanced technologies and strategies for optimization and dispersion of fillers for improved properties will be required in the future.

References

1. Chen G, Zhao W (2010) Rubber/graphite nanocomposites, chapter 19. In: Rubber nanocomposites: preparation, properties and applications. Wiley, Singapore
2. Pramanik PK, Khastgir D, Saha TN (1991) Electro magnetic interference shielding by conductive nitrile rubber composites containing carbon fillers. J Elastomers Plast 23(4):345–361
3. Mattson B, Stenberg B (1992) Electrical conductivity of thermo-oxidatively-degraded EPDM rubber. Rubber Chem Technol 65(2):315–328
4. Chen X, Jiang Y, Wu Z, Li D, Yang J (2000) Morphology and gas-sensitive properties of polymer based composite films. Sens Actuators B Chem 66(1):37–39
5. Blow CM, Hepburn C (1982) Rubber technology and manufacture, 2nd edn. Butterworth Scientific, UK

6. Yao S, Zhu Y (2015) Nanomaterial-enabled stretchable conductors: strategies. Mater Devices Adv Mater. doi:10.1002/adma.201404446
7. Cheng T, Zhang Y, Lai WY, Huang W (2015) Stretchable thin- film electrodes for flexible electronics with high deformability and stretchability. Adv Mater. doi:10.1002/adma.201405864
8. Marshall JE, Gallagher S, Terentjev EM, Smoukov SK (2014) Anisotropic colloidal micro muscles from liquid crystal elastomers. J Am Chem Soc 136:474–479
9. Kaltenbrunner M, Sekitani T, Reeder J, Yokota T, Kuribara K, Tokuhara T, Drack M, Schwodiauer R, Graz I, Gogonea SB, Bauer S, Someya T (2013) An ultra-lightweight design for imperceptible plastic electronics. Nature 499:458–463
10. Lipomi DJ, Tee BC-K, Vosgueritchian M, Bao ZN (2011) Stretchable organic solar cells. Adv Mater 23(15):1771–1775
11. Osman HM, Abdel Chani SA, Madkour TM, Mohammed AR (2000) Stress relaxation in carbon black loaded butyl rubber. J Appl Polym Sci 77:1067–1076
12. Chodak I, Omastova M, Pionteck J (2001) Relation between electrical and mechanical properties of conducting polymer composites. J Appl Polym Sci 82:1903–1906
13. Omastova M, Podhradska S, Prokes J, Janigova I, Stejskal J (2003) Thermal ageing of conducting polymeric composites. Polym Degrad Stab 82:251–256
14. Krupa I, Chodak I (2001) Physical properties of thermoplastic/graphite composites. Eur Polym J 37:2159–2168
15. Das NC, Chaki TK, Khastgir D (2002) Effect of processing parameters, applied pressure and temperature on the electrical resistivity of rubber-based conductive composites. Carbon 40:807–816
16. Sichel EK (1982) Carbon black polymer composites. Marcel Dekker, NY, p 214
17. Shioyama H, Akita T (2003) A new route to carbon nanotubes. Carbon 41:179–181
18. Tasis D, Tagmatarchis N, Bianco A, Prato M (2006) Chemistry of carbon nanotubes. Chem Rev 106:1105–1136
19. Mietta JL, Jorge GE, Perez OE, Maeder T, Negri RM (2013) Superparamagnetic anisotropic elastomer connectors exhibiting reversible magneto-piezoresistivity. Sens Actuators A Phys 192:34–41
20. Mietta JL, Ruiz MM, Antonel PS, Perez OE, Butera A, Jorge GE, Negri RM (2012) Anisotropic magnetoresistance and piezoresistivity in structured Fe_3O_4-silver particles in PDMS elastomers at room temperature. Langmuir 28:6985–6996
21. Lee S, Shin S, Lee S, Seo J, Lee J, Son S, Cho HJ, Algadi H, Al-Sayari S, Kim DE, Lee T (2015) Ag nanowire reinforced highly stretchable conductive fibers for wearable electronics. Adv Funct Mater. doi:10.1002/adfm.201500628
22. Sung Y, El-Tantawy F (2002) Novel smart polymeric composites for thermistors and electromagnetic wave shielding effectiveness from TiC loaded styrene-butadiene rubber. Macromol Res 10(6):345–358
23. Gwaily SE, Nasr GM, Badawy MM (2001) Thermal and electrical properties of irradiated styrene butadiene rubber-metal composites. Egypt J Sol 24(2):193–205
24. Dannenberg EM (1978) In encyclopedia of chemical technology, vol 4, 3rd edn. Wiley, NY, p 631
25. Lyon F (1985) Encyclopedia of polymer science and engineering, vol 2, 2nd edn. Wiley, NY, p 623
26. Al-Hartomy OA, Al-Ghamd A, Dishovsky N, Malinova P, El-Tantawy F (2012) Some factors determining the volume resistivity of filled natural rubber-based nanocomposites. Prog Rubber Plast Recycl Technol 28:95–110
27. Luo H, Kluppel M, Schneider H (2004) Study of filled SBR elastomers using NMR and mechanical measurements. Macromolecules 37:8000–8009
28. Morsy RM, Ismaiel MN, Yehia AA (2013) Conductivity studies on acrylonitrile butadiene rubber loaded with different types of carbon blacks. Int J Mater Meth Technol 1(4):22
29. Podhradska S, Prokes J, Omastova M, Chodak I (2009) Stability of electrical properties of carbon black-filled rubbers. J Appl Polym Sci 112:2918–2924

30. Janzen J (1975) On the critical conductive filler loading in antistatic composites. J Appl Phys 46:966
31. Kawazoe M, Ishida H (2008) A new concept for nanoparticle distribution in SBR/NBR blend solution and films via molecular confinement. Macromolecules 41:2931–2937
32. Gubbels F, Jerome R, Vanlathem E, Deltour R, Blacher S, Brouers F (1998) Kinetic and thermodynamic control of the selective localization of carbon black at the interface of immiscible polymer blends. Chem Mater 10:1227–1235
33. Cheah K, Forsyth M, Simon GP (2000) Processing and morphological development of carbon black filled conducting blends using a binary host of poly (styrene co-acrylonitrile) and poly (styrene). J Polym Sci Part B Polym Phys 38:3106–3119
34. Zhang C, Han HF, Yi XS, Asai S, Sumita M (1999) Selective location of the filler and double percolation of Ketjenblack filled high density polyethylene/isotactic polypropylene blends compos. Interfaces 6:227–236
35. Feng JY, Chan CM (1998) Carbon black-filled immiscible blends of poly (vinylidene fluoride) and high density polyethylene: electrical properties and morphology. Polym Eng Sci 38:1649–1657
36. Mamunya YP (1999) Morphology and percolation conductivity of polymer blends containing carbon black. Macromol Sci Phys 38:615–622
37. Diaz R, Diani J, Gilormini P (2014) Physical interpretation of the Mullins softening in a carbon-black filled SBR. Poymer 55:4942–4947
38. Wang L, Zhao S (2010) Study on the structure-mechanical properties relationship and antistatic characteristics of SSBR composites filled with SiO_2/CB. J Appl Polym Sci 118:338–345
39. Karasek L, Meissner B, Asai S, Sumita M (1996) Percolation concept: polymer-filler gel formation, electrical conductivity and dynamic electrical properties of carbon-black-filled rubbers. Polym J 28(2):121–126
40. He M, Yuan LX, Zhang WX, Hu XL, Huang YH (2011) Enhanced cyclability for sulfur cathode achieved by a water-soluble binder. J Phys Chem C 115:15703–15709
41. Peddini SK, Bosnyak CP, Henderson NM, Ellison CJ, Paul DR (2014) Nanocomposites from styrene-butadiene rubber (SBR) and multiwall carbon nanotubes (MWCNT) part 1: morphology and rheology. Polymer 55:258–270
42. Hu GJ, Zhao CG, Zhang SM, Yang MS, Wang ZG (2006) Low percolation thresholds of electrical conductivity and rheology in poly (ethylene terephthalate) through the networks of multi-walled carbon nanotubes. Polymer 47(1):480–488
43. Abdel-Goad M, Potscheke J (2005) Rheological characterization of melt processed polycarbonate-multiwalled carbon nanotube composites. J Nonnewton Fluid 128(1):2–6
44. Alig I, Skipa T, Lellinger D, Potscheke P (2008) Destruction and formation of a carbon nanotube network in polymer melts: rheology and conductivity spectroscopy. Polymer 49(16):3524–3532
45. Das A, Stockelhuber KW, Jurk R, Fritzsche J, Kluppel M, Heinrich G (2009) Coupling activity of ionic liquids between diene elastomers and multi-walled carbon nanotubes. Carbon 47(14):3313–3321
46. McNally T, Ptscheke P, Halley P, Murphy M, Martin D, Bell SEJ et al (2005) Polyethylene multiwalled carbon nanotube composites. Polymer 46(9):8222–8232
47. Li Y, Shimizu H (2009) Toward a stretchable, elastic, and electrically conductive nanocomposite: morphology and properties of poly [styrene-b-(ethylene-co-butylene)-b-styrene]/multiwalled carbon nanotube composites fabricated by high-shear processing. Macromolecules 42:2587–2593
48. Pedroni LG, Araujo JR, Felisberti MI, Nogueira F (2012) Nanocomposites based on MWCNT and styrene–butadiene–styrene block copolymers: effect of the preparation method on dispersion and polymer–filler interactions. Compo Sci Technol 72:1487–1492
49. Tsuchiya K, Sakai A, Nagaoka T, Uchida K, Furukawa T, Yajima H (2011) High electrical performance of carbon nanotubes/rubber composites with low percolation threshold prepared with a rotation–revolution mixing technique. Compos Sci Technol 71:1098–1104

50. Das A, Kasaliwal GR, Jurk R, Boldt R, Fischer D, Stockelhuber KW, Heinrich G (2012) Rubber composites based on graphene nanoplatelets, expanded graphite, carbon nanotubes and their combination: a comparative study. Compo Sci Technol 72:1961–1967
51. Araby S, Saber N, Ma X, Kawashima N, Kang H, Shen H, Zhang L, Xu J, Majewski P, Ma J (2015) Implication of multi-walled carbon nanotubes on polymer/graphene composites. Mater Desig 65:690–699
52. Dreyer RD, Park S, Bielawski CW, Ruoff RS (2010) The chemistry of graphene oxide. Chem Soc Rev 39:228–240
53. Wang G, Yang J, Park J, Gou X, Wang B, Liu H et al (2008) Facile synthesis and characterization of graphene nanosheets. J Phys Chem C 112:8192–8195
54. Li X, Wang X, Zhang L, Lee S, Dai H (2008) Chemically derived, ultrasmooth graphene nanoribbon semiconductors. Science 319:1229–1232
55. Blake P, Brimicombe PD, Nair RR, Booth TJ, Jiang D, Schedin F et al (2008) Graphene-based liquid crystal device. Nano Lett 8:1704–1708
56. www.wikipedia.org/wiki/Graphene
57. Novoselov KS, Geim AK, Morozov SV, Jiang D, Zhang Y, Dubonos SV et al (2004) Electric field effect in atomically thin carbon films. Science 306:666–669
58. Kim H, Abdala AA, Maosko CW (2010) Graphene/polymer nanocomposites. Macromolecules 43:6515–6530
59. Kuilla T, Bhadra S, Yao D, Kim NH, Bose S, Lee JH (2010) Recent advances in graphene based polymer composites. Prog Polym Sci 35:1350–1375
60. Sengupta R, Bhattacharya M, Bandyopadhyay S, Bhowmick AK (2011) A review on the mechanical and electrical properties of graphite and modified graphite reinforced polymer composites. Prog Polym Sci 36:638–670
61. Sadasivuni KK, Ponnamma D, Thomas S, Grohens Y (2014) Evolution from graphite to graphene elastomer composites. Prog Poym Sci 39:749–780
62. Araby S, Meng Q, Zhang L, Zaman I, Majewski P, Ma J (2015) Elastomeric composites based on carbon nanomaterials. Nanotechnology 26:112001
63. Ozbas B, O'Neill CD, Register RA, Aksay IA, Prud'homme RK, Adamson DH (2012) Multifunctional elastomer nanocomposites with functionalized graphene single sheets. J Polym Sci Part B Polym Phy 50:910–916
64. Steurer P, Wissert R, Thomann R, Muelhaupt R (2009) Functionalized graphenes and thermoplastic nanocomposites based upon expanded graphite oxide. Macromol Rapid Commun 30:316–327
65. Liu X, Kuang W, Guo B (2015) Preparation of rubber/graphene oxide composites with in-situ interfacial design. Polymer 56:553–562
66. Xing W, Tang M, Wu J, Huang G, Li H, Lei Z, Fu X, Li H (2014) Multifunctional properties of graphene/rubber nanocomposites fabricated by a modified latex compounding method. Compo Sci Technol 99:67–74
67. Hummers WS, Offeman RE (1958) Preparation of graphitic oxide. J Am Chem 80:1339
68. Schopp S, Thomann R, Ratzsch KF, Kerling S, Altstadt V, Mulhaupt R (2013) Functionalized graphene and carbon materials as components of styrene-butadiene rubber nanocomposites prepared by aqueous dispersion blending. Macromol Mater Eng 299(3):319–329
69. Ozbas B, O'Neill CD, Register RA, Aksay IA, Prud'homme RK, Adamson DH (2012) Multifunctional elastomer nanocomposites with functionalized graphene single sheets. J Polym Sci Part B Polym Phy 50:910–916
70. Song SH, Jeong HK, Kang YG (2010) Preparation and characterization of exfoliated graphite and its styrene butadiene rubber nanocomposites. J Indust Eng Chem 16:1059–1065
71. Araby S, Zhang L, Kuan HC, Dai JB, Majewski P, Ma J (2013) A novel approach to electrically and thermally conductive elastomers using graphene. Polymer 54:3663–3670
72. Zhang H, Wang C, Zhang Y (2015) Preparation and properties of styrene-butadiene rubber nanocomposites blended with carbon black-graphene hybrid filler. J Appl Polym Sci. doi:10.1002/APP.41309

73. Fugetsu B, Sano E, Yu H, Mori K, Tanaka T (2010) Graphene oxide as dyestuffs for the creation of electrically conductive fabrics. Carbon 48:3340–3345
74. Sherman RD, Middelman LM, Jacobs SM (1983) Electron transport processes in conductor-filled polymers. Polym Eng Sci 23(1):36–46
75. Ruiz MM, Marchi MC, Perez OE, Jorge GE, Fascio M, D'Accorso N, Negri RM (2015) Structured elastomeric submillimeter films displaying magneto and piezo resistivity. Polym Phy 53:574–586
76. Ivanekyo D, Toshchevikov VP, Saphiannikova M, Heinrich G (2011) Magneto-sensitive elastomers in a homogeneous magnetic field: a regular rectangular lattice model. Macromol Theory Simul 20:411–424
77. Shahrivar K, De Vicente J (2013) Thermoresponsive polymer-based magneto-rheological (MR) composites as a bridge between MR fluids and MR elastomers. Soft Matter 9:11451–11456
78. Danas K, Kankanala SV, Triantafyllidis N (2012) Experiments and modeling of iron-particle-filled magnetorheological elastomers. J Mech Phys Solids 60:120–138
79. Bica I, Liu YD, Choi HJ (2012) Magnetic field intensity effect on plane electric capacitor characteristics and viscoelasticity of magnetorheological elastomer. Colloid Polym Sci 290:1115–1122
80. Mietta JL, Jorge GE, Negri RM (2014) A flexible strain gauge exhibiting reversible piezoresistivity based on an anisotropic magnetorheological polymer. Smart Mater Struct 23:85026–85038
81. Kirkpatrick S (1973) Percolation and conduction. Rev Mod Phys 45:574
82. Schettini ARA, Khastigir D, Soares BG (2012) Microwave dielectric properties and EMI shielding effectiveness of poly (styrene-b-styrene-butadiene-styrene) copolymer filled with PAni, Dodecylbenzenesulfonic acid and carbon black. Polym Eng Sci 52(9):2041–2048